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'AUTO-RECORM' - BUGS: ALGORITHMS AND COOPERATIVE BEHAVIOR FOR ENHANCING UXO CLEARANCE

by

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13. ABSTRACT (Maximum 200 words)

This report deals with the use of a multi-vehicle robotic approach to PUCA operations for UXO clearance. The NAVEODTECHDIV has the 'RECORM' vehicle - a tele-operated vehicle enabling the user to search and visually detect and classify UXO targets. The operation is being automated and combined with the use of the BUGS system of low cost robots which perform the Pick-Up and Carry Away (PUCA) operations. This report provides the results of studies that look at the system effectiveness in terms of time to clear five different scenarios involving sub-munition clusters. The use of a dynamic zone allocation (DZA) strategy is found to be superior when the BUGS vehicles are used alone. However, the combined use of RECORM to do targeting, followed by BUGS using directed searching provides the best of all options.

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'AUTO-RECORM' / BUGS: Control Algorithms and Cooperative Behavior for Enhancing UXO Clearance

REPORT ON STUDIES WITH UXO CLEARANCE TECHNOLOGIES

A. J. Healey and J. Kim

NAVAL POSTGRADUATE SCHOOL
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ABSTRACT

This report deals with the effectiveness of using a multi vehicle fleet of robots to perform UXO search, pick-up, and carry away (PUCA) operations. The class of problems addressed relates to range remediation and field clearance issues with small submunitions. It is assumed that small robots (BUGS), studied in previous work, would be developed with the capacity to detect and pick up submunitions. The NAVEODTECHDIV also has a vehicle called 'RECORM' that is a teleoperated vehicle with video camera which is designed to perform reconnaissance tasks by remote control. The video camera can be used with long field of view to perform rapid area search and then with fine field of view to perform classification. This vehicle is now being automated producing the AUTO-RECORM capability. Since it will be a high valued asset, it is generally thought that the PUCA part of clearance would be performed by low cost robots i.e., BUGs. How to best use the capabilities provided by both assets in a cooperative manner is not known, but is the subject of this work.

Five scenarios are studied based on the idea that the typical distribution of UXO submunitions lies in clusters rather than in a uniform distribution. Previous work has assumed uniformly distributed fields. With clustered submunitions, the problem is more difficult because it is not known apriori, where the clusters lie. One solution is to use AUTORECORM to perform rapid area survey, detection and classification, and provide target locations. The BUGS then prosecute targets as their locations become available while the more expensive asset moves on without attempting the pick up. Alternatively, using BUGS alone, these slow moving low cost assets first attempt to find clusters, and after a cluster is established, through inter vehicle communications, a location for the cluster is established and vehicles available for re-targeting are tasked to home into the newly established cluster. Thus the search area is dynamically reduced as the scene unfolds. Finally, the last option using low cost assets in large numbers, searching the whole field using no apriori knowledge with no inter-vehicle communication is studied and found to be too time consuming.

It is shown that the combined use of both assets will be the most effective system in terms of clearance performance, while the use of low cost BUGS will be more effective if the use of inter BUG communications and DZA is used.

ACKNOWLEDGMENTS

The authors would like to express particular appreciation to Mr. Chris DeBolt of the Naval Explosive Ordnance Disposal Technical Division, Research and Development Department, and to the Marine Corps, and the Office of Naval Research (Dr. Tom Swean) for the underlying financial support of this project.

TABLE OF CONTENTS

1. INTRODUCTION

In previous studies [1], minefield and UXO clearance operations have been simulated using multi vehicle systems where both random and directed searching techniques are used for clearance operations. Both PUCS and BIP operations were considered. The advantage of the prior knowledge of the location of prospective targets, even though it may be imprecise, has been shown to be significant. Basically, the search area is reduced to that defined by the imprecision in the targeting location information so that clearance times are reduced. In this work, it is recognized that UXO fields are not characterized by uniform distributions but rather, UXO submunition fields are composed of clusters of higher concentrations resulting from an aircraft drop. There may also be lower concentrations of UXO submunitions in the general area. This work then, looks at the combined use of a high valued asset to perform detection and classification in clustered areas, while low valued assets are used to follow up and perform the PUCA operations.

The problem with clustered munition drops is that the location of the clusters are not known to begin with. The high valued asset must also be rapidly mobile to perform wide area survey and identify the locations of the clusters. The low cost assets then prosecute the clustered areas to perform PUCA.

1.1 BUGS and Auto-RECORM Scenarios

Five scenarios have been defined for the purpose of this study. The operating area is a 150*m* x 150*m* square with a collection site at the center of the field. The location of the cluster of UXO targets is not known and is randomized .

Phase I. Assume one cluster, circular in shape, with a diameter of 25*m*. The target density within the cluster is 0.0667 per square meter, for approximately 44 targets within cluster. The center of the cluster is randomly placed within the operating area, though the entire cluster shall be contained within the operating area. In this phase, there are on natural / man made obstacles.

Phase II. Add randomly distributed targets to Phase I with a density of 0.0015 per square meter. This will add approximately 33 more targets to the Phase I senario.

Phase III. Add a second randomly placed cluster to Phase II, as in Phase I.

Phase IV. Add randomly occurring obstacles to Phase III.

Phase V. Add a third randomly placed cluster to V, as in Phase I and Phase III.

1.2 DZA and Cooperative Behaviors

Dynamic Zone Allocation (DZA) is a search technique explored here to efficiently find unknown targets that may be encountered in clusters within a larger area. An advantage of DZA is that a number of targets can be found in a reduced amount of time, a time that is less than that to perform a randomized sweep of the entire area.

The searchers disperse, and randomly search for targets. As one target is found, this is assumed to be part of a cluster, and the location is designated as the center of dynamic Zone (DZ). The size of DZ may be scaled to the overall size of the entire operation area to search. Other searchers are summoned to the newly defined DZ to perform random searches within the zone. The simplest, and a reasonable assumption of cluster shape, and thus DZ shape, is a circle, If a competent navigation and communication system is available, the center of the DZ can be transmitted to other searchers.

As additional targets are found within the DZ, the defined center of the DZ is adjusted to be the new control of the DZA. The size of the DZ, may be dynamic at this point, too, expanding slightly to account for the moving center.

After some predefined time (a time-out), if no targets are found within the DZ, the searchers are dispersed again to randomly search the entire operating area, and the DZ is decommissioned. As another new target is found, this becomes the center of a new DZ.

1.3 Shared Target Lists and Time Outs

The cooperative nature of BUGs will also be examined in scenarios in which a target list is *assumed to be available* before the individual BUGs go out and pick up and carry away the target to disposal place. Instead of assigning specific targets to each BUG, all BUGs can operate on all the targets. A shared dynamic target list is used, so that the BUGs can determine which target on the list is closest, and navigate to that target area and search that target in that small area. As the targets are found, they are removed from the shared target list.

This technique should be most efficient when there is a good initial dispersion of the BUGs, so the probability that many BUGs are searching for the same target is minimized. This problem of many searching for one target may be encountered as targets are dropped off at the UXO disposal place, located at the center of the operation field.

To solve this problem, a target is removed from the shared target list when a BUG decides to search for it. This eliminates a potential problem of many BUGs interfering with each other as they approach one target. A time-out needs to be employed wherein the target is placed back onto shared list if it is not found by the searcher within an allotted time (3 minutes). Occasionally, if particular searchers cannot find a particular target, it may be cleared by a one searcher by default, or be unattainable, so that no further searching must be declared.

1.4 Scope of work

The scope of work includes a study of five different scenarios using three different systems. The first system assumes that BUGs alone are used in random searching through the entire field of interest. The second system looks at automation of the RECORM vehicle with the purpose of establishing targets of interest rapidly. The vehicle is equipped with a video camera that can change its focal length from wide angle view for detection, followed by narrow angle view at close up positions for classification details. The third system considered is to use a fleet of BUGs vehicles with the efficiency enhancing effects of Dynamic Zone Allocation.

The work covers Monte Carlo simulation of these multi-robot scenarios in which 1000 replications of each system / scenario are conducted so that meaningful statistical responses are obtained.

2.0 USE OF BUGS ALONE

In this section, we will discuss the results of the simulation for the given scenario using the BUGs alone. In this simulation, we modeled the navy BUG. The 'Navy' BUG has been designed with four wheels for traction with differential wheel speed as the steering mechanism. In this scenario, the BUG vehicles are assumed to be equipped with GPS units so that, in differential mode, the vehicles will know their location in the search area within 14 cm. Vehicle transit speed is 1.5 ft/sec (45.72 cm/sec). The target detection radius is assumed in these examples to be 0.625 ft (19.05 cm), meaning that any target that is encountered within this radius is considered to be detected. The obstacle detection range is assumed to be 1 ft (30.48 cm). It has obstacle avoidance capability. Its obstacle avoidance method favored a right turning move whenever it encounters an obstacle. The simulation is based on a one second time step update.

The first section gives results of the pick up and carry away (PUCA) simulation using the random search method within the entire field. The entire field area is 150m by 150m and is 22500m^2. Moving at the speed of 0.45.72cm/sec with a detection radius of 19.05 cm. each side, the sweep rate is 0.174m^2/sec, with a characteristic time of 35 vehicle-hours. Searching to a 100% area coverage within a reasonable time duration such as not more than 4 hours therefore requires 9 vehicles. This however, would leave *no overlap* of coverage. While this may be possible, the potential for holidays means that an overlapping search is more realistic. With three to one overlap, the time to detect all targets would be 3*3.5 hours for 10 vehicles - over 600 minutes. This initial calculation leaves no time for PUCA and obstacle avoidance. A randomized search produces similar results and these can be improved using DZA.

The second section gives results of simulations of the Dynamic Zone Allocation (DZA) search technique. These two search techniques can be used if no apriori target locations are available. In the third section, the cooperative nature of BUGS/AUTO RECORM will be examined in a scenario in which apriori target information is available from the use of AUTO RECORM.

2.1 Random Search

The random search and pick up carry away (PUCA) simulation program developed earlier in [1], is tested with the cluster scenario field. In this simulation, we assumed that no target location is known a priori. We modeled the navy BUG. The Navy BUG has been designed with four wheels for traction with differential wheel speed as the steering mechanism. In this scenario, the BUG vehicles are assumed to be equipped with GPS units so that, in differential mode, the vehicles will know their location in the search area within 14 cm. Vehicle transit speed is 1.5 ft/sec (45.72 cm/sec). The target detection radius is assumed in these examples to be 0.625 ft (19.05 cm), meaning that any target that is encountered within this radius is considered acquired. The obstacle detection range is assumed to be 1 ft (30.48 cm). The search method is based on a randomized heading change every 5 second of travel and it has obstacle avoidance capability. Its

obstacle avoidance method favored a right turning move whenever it encountered obstacle. Step simulation is based on time (one second) for each step.

Figure 2-1 through figure 2-10 shows that the results of simulation runs using 5 BUGs and 10 BUGs in the 5 phase test scenario with an assumed perfect sensor.. Figure 2.1-1, 3, 5, 7,9 shows the example of the BUG paths for each phase of the scenario for the random search technique, respectively. Figure 2.1-2, 4, 6, 8,10 shows the performance results of the random search using 5 and 10 BUGs for each phase of the scenario respectively. The data plotted in these figures represents the avaerage responses over 1000 individual replications of each scenario.

Examination of these clearance performance results show some interesting features. First, for every scenario, between 70 and 80% of the clearance is performed within 600 minutes. Considering that the time for 100% area coverage with no overlap is 3.5 hours for 10 vehicles (210 minutes), it is not surprising that 80% clearance takes 600 minutes. However, not only is time taken for the added overlap due to random search, but the result also includes time for vehicle / vehicle obstacle avoidance and for the PUCA operations.

It is noted that after 600 minutes, the scenario for Phase I is relatively less developed than Phase II and Phase IV and V. The explanation is that with Phase I the distribution of targets is highly clustered while the other Phases are more well distributed throughout the field. Thus relatively expressed as a percentage of clearance, the cleared values of phase I is less than phase VI and V. It should be remembered that in Phase V with 3 clusters, there are approximately three times the number of UXO objects to be cleared.

2.2 Comments:

In spite of the randomized nature of the PUCA operation, 10 vehicles working the entire field complete almost 75% of their necessary work within 600 minutes - 10 hours. However, since the endurance of small robots is not likely to exceed 4 hours, more than 10 BUGs would be required. In fact, using the same clearance rate data, only 85% could be cleared even with 20 BUGs working Phase I.

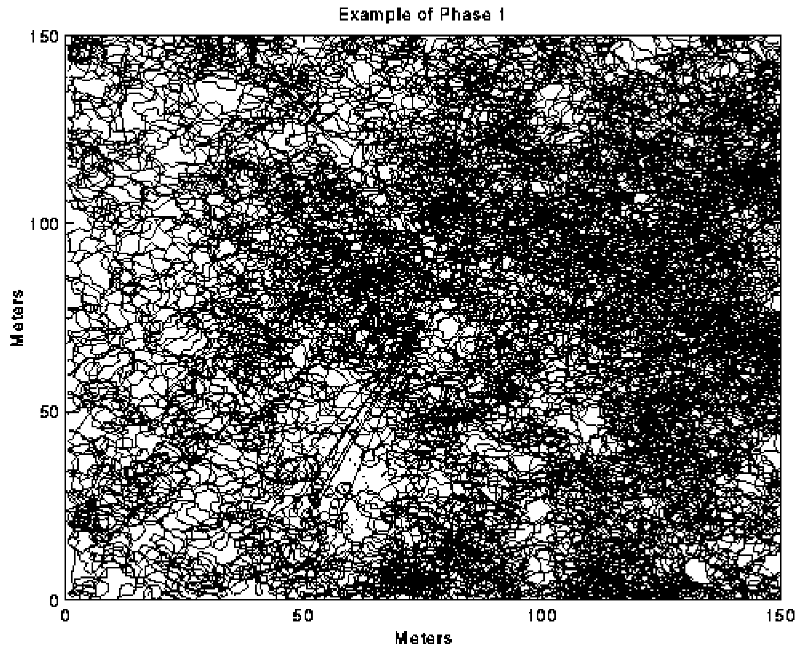


Figure 2.1-1. Example of BUGS path for the Phase I

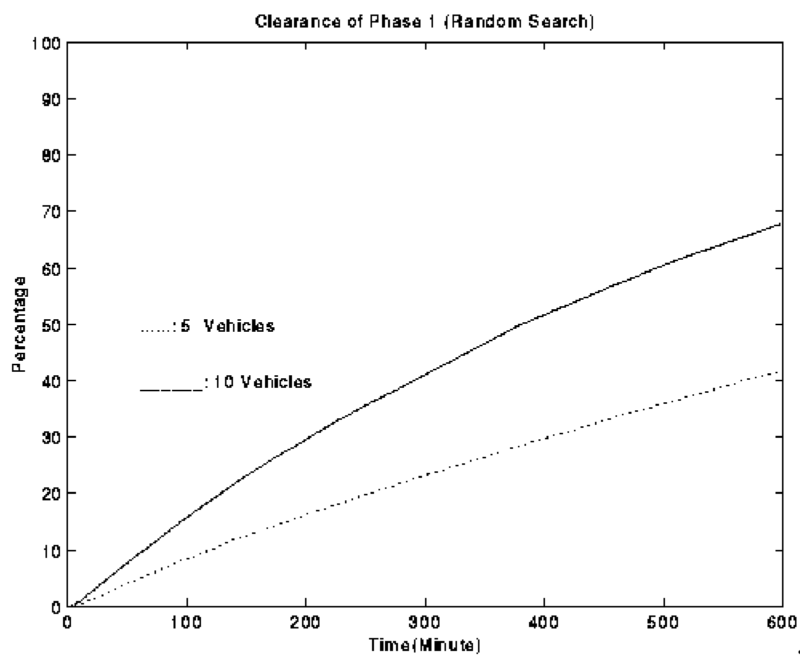


Figure 2.1-2. Clearance Rate for BUGS for the Phase I. Search and PUCA

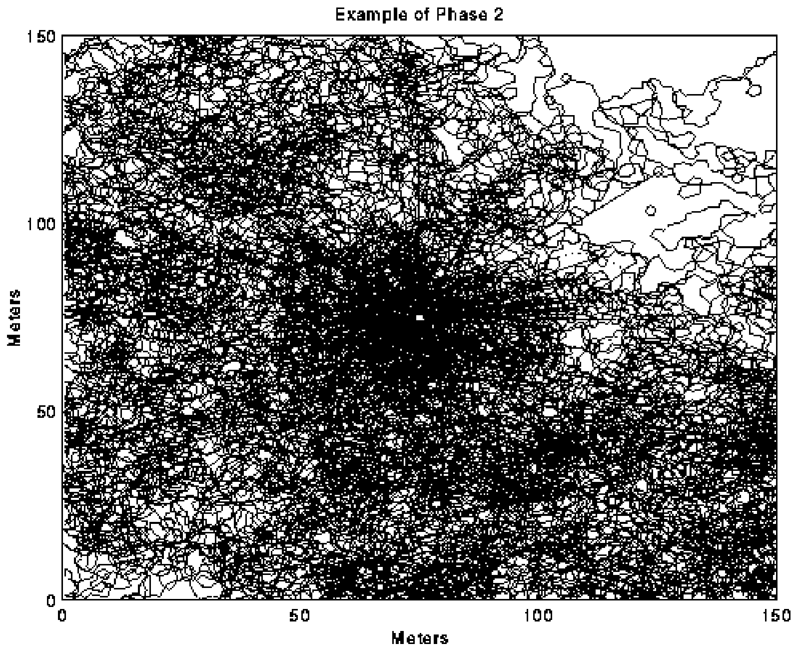


Figure 2.1-3. Example of BUGS path for the Phase II.

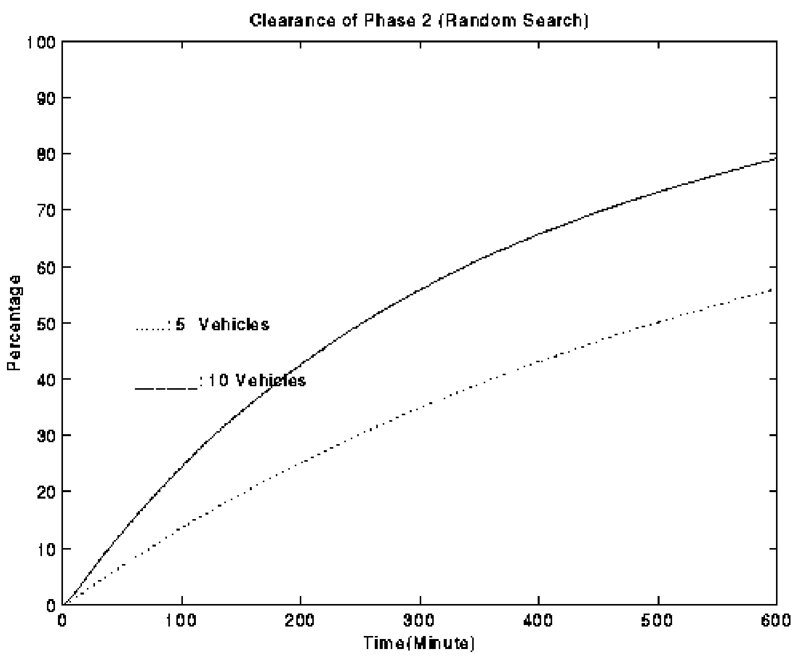


Figure 2.1-4. Clearance rate for BUGS for the Phase II.

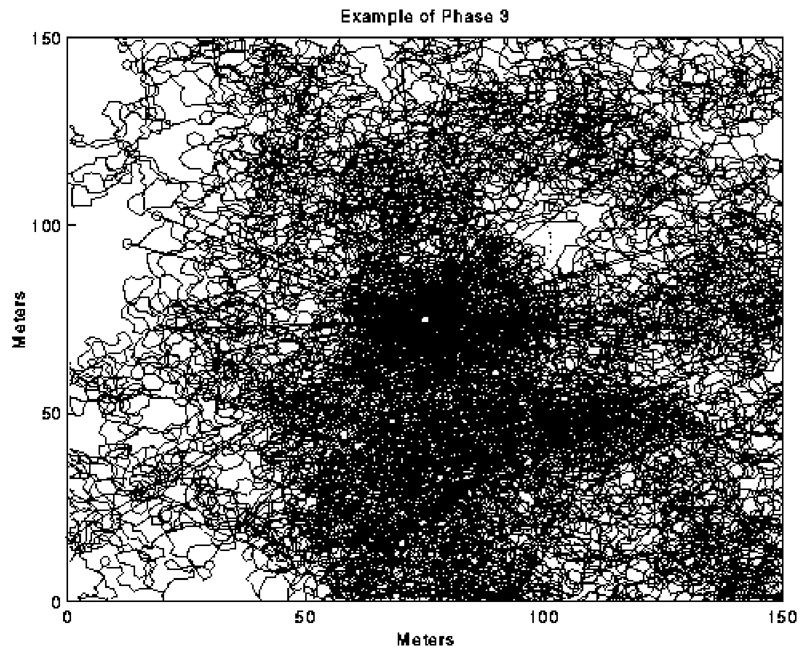


Figure 2.1-5. Example of BUGS path for the Phase III.

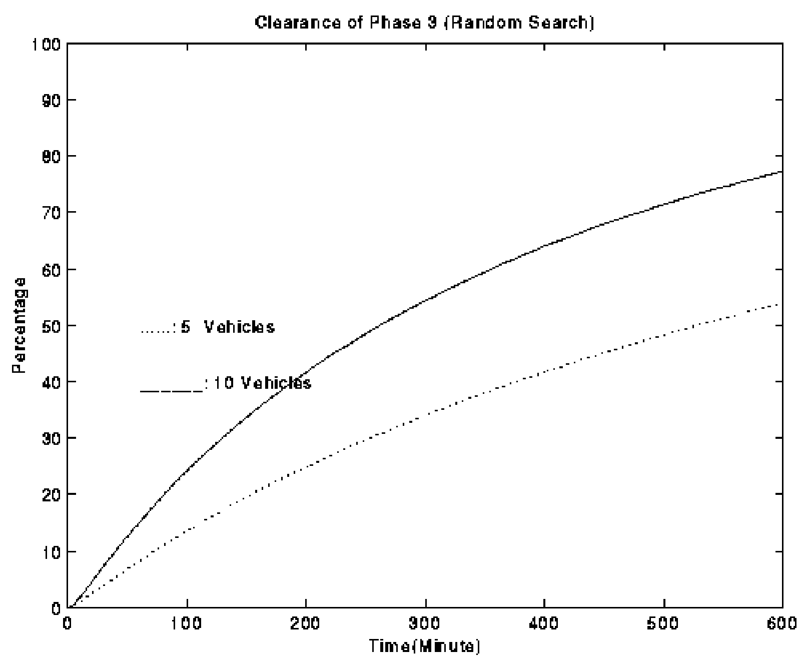


Figure 2.1-6. Clearance rate for BUGS for the Phase III.

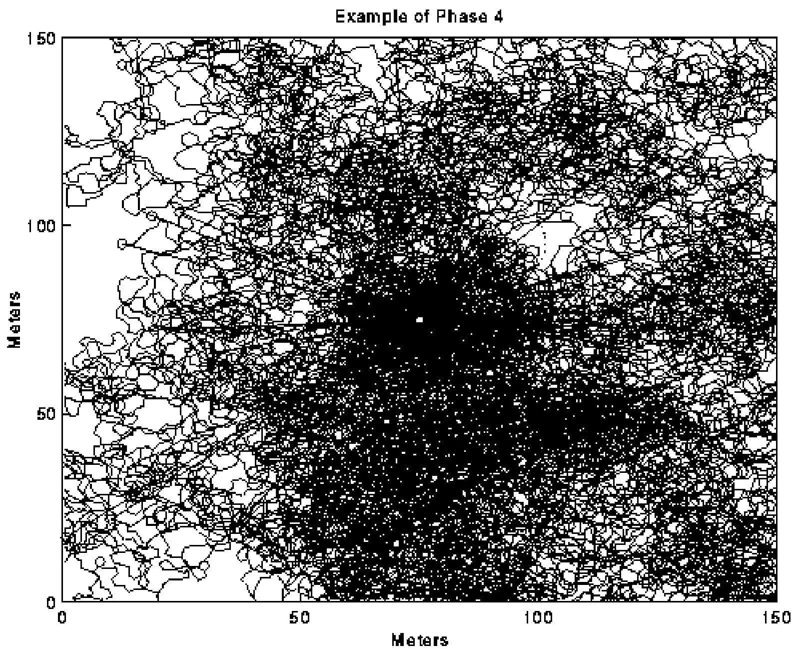


Figure 2.1-7. Example of BUGS path for the Phase IV.

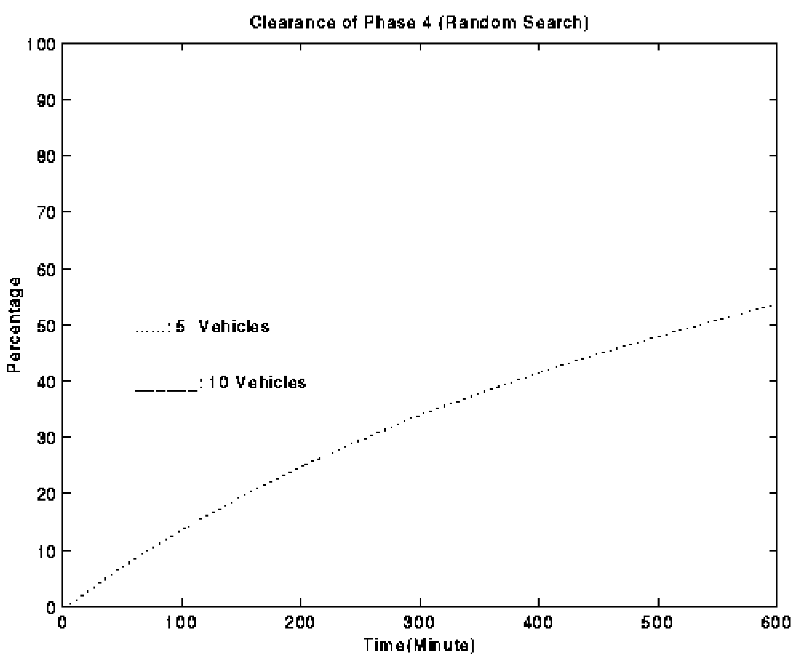


Figure 2.1-8. Clearance rate for BUGS for the Phase IV.

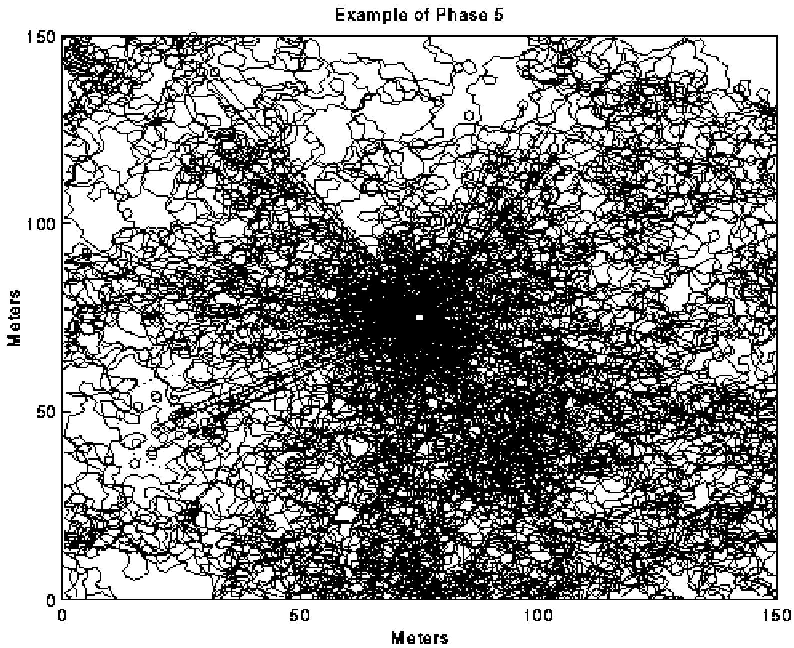


Figure 2.1-9. Example of BUGS path for the Phase V

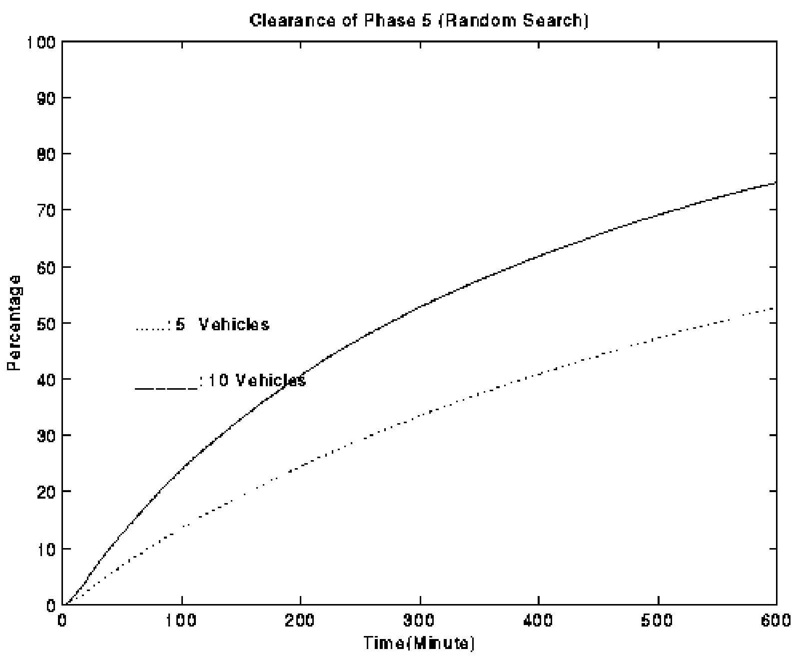


Figure 2.1-10. Clearance rate for BUGS for the Phase V

2.3 BUGs with Shared Target List

Since the use of BUGs alone with *no apriori* information regarding target distributions is inefficient and would not be practical at the present time, the next section describes a simulation for the cooperative nature of BUGs with *apriori* known target

locations. A target list is available before the individual BUGs go out and pick up and carry away the target to disposal place. Instead of assigning specific targets to each BUGs, all BUGs can operate on all the targets. A shared target list is used, so that the BUGs can determine which target on the list is closest, and navigate to that target area and search that target in that small area. As the target are found, they are removed from the shared target list. This technique should be most efficient when there is a good initial dispersion of the BUGs, so the probability that many BUGs are searching for the same target is minimized. This problem of many searching for one target may be encountered as targets are dropped off at the UXO disposal place which is located at the center of the operation field.

To solve this problem, a target is removed from shared target list when a BUG decides to search for it. This eliminates a potential problem of many BUGs interfering with each other as they approach one target. A time-out must be employed wherein the target is placed back onto shared list if it is not found by the searcher within an allotted time (3 minutes). And if other searcher cannot find a particular target, it may be cleared by a searcher, or unattainable, and no further searching occurs.

In this test, the BUGs vehicles are assumed to be equipped with GPS units so that, in differential mode, the vehicles will know their location in the search area within about one meter. The pre-survey is accomplished by gathering GPS fixes of all the UXO found in the search area.

In this simulation, we assume that vehicle velocity is 0.4 *m/sec* during navigation and 0.2 *m/sec* within 1 *m* radius search area. The detection radius is assumed to be 20 *cm*, meaning that any target is encountered within this radius is considered acquired. We assume that the location and size of the obstacles is not known. Obstacle detection radius is assumed to be 1.0 *m*.

Figure 2.3-1, 3, 5, 7, and 9, show that how vehicles operate the PUCA operation on the test field. The PUCA operation using shared target list is following, First, the vehicle obtains a nearest target fix from vehicle position (home), and it navigates to the UXO fix using GPS unit and compass with velocity 0.4 m/sec. With error on both the GPS and compass, the only capable of placing the vehicle within the vicinity of the UXOfix. If it is within the 1 m radius defined search area for the chosen UXO fix, the vehicle speed is reduced to 0,2 m/sec and navigate to vicinity of the target fix. It then performs a search operation. We used a *spiral search* method in this simulation. Spiral search is optimal where the search area is circular in nature.

If a vehicle detects the target, the UXO is assumed to be acquired by the vehicle. Following that action, the vehicle is assumed to change its heading to the disposal place which is located in the center of the test field. The vehicle then navigate to the collection place, avoiding both unexpected obstacle and other not yet acquired targets while enroute to the disposal area. When the vehicle enters the drop-off area, it drop off the UXO, turn around, and navigates to the nearest target to continue searching. If none are left, it

returns to home base. Figure 2.3-2, 4, 6, 8, and 10 shows the performance result using five and ten BUGs for the five phase respectively.

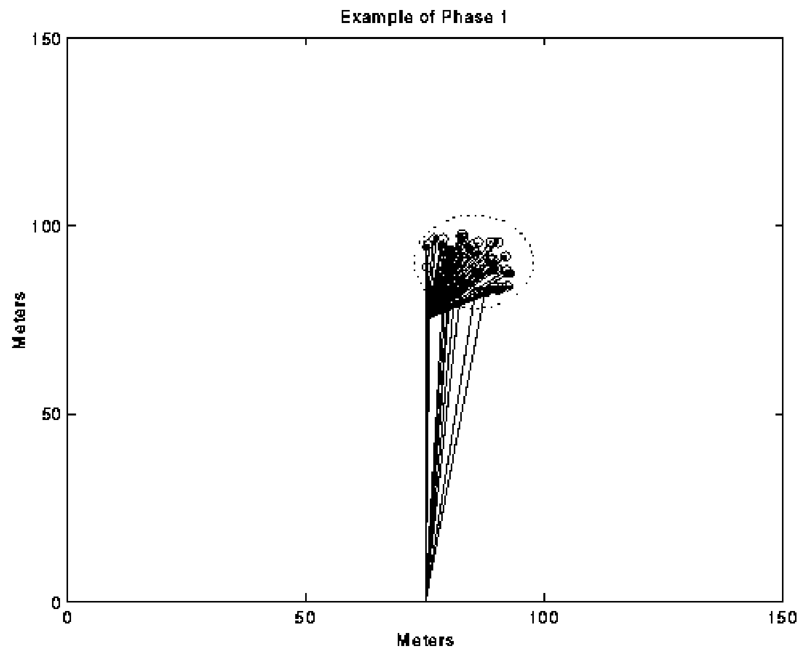


Figure 2.3-1. Example of BUGS path for the Phase I

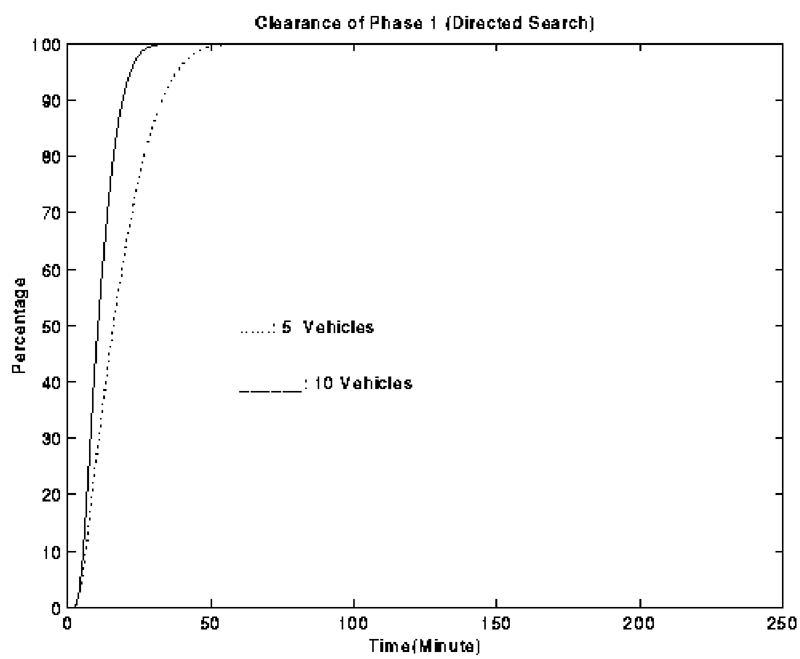


Figure 2.3-2. Clearance rate for BUGS for the Phase I.

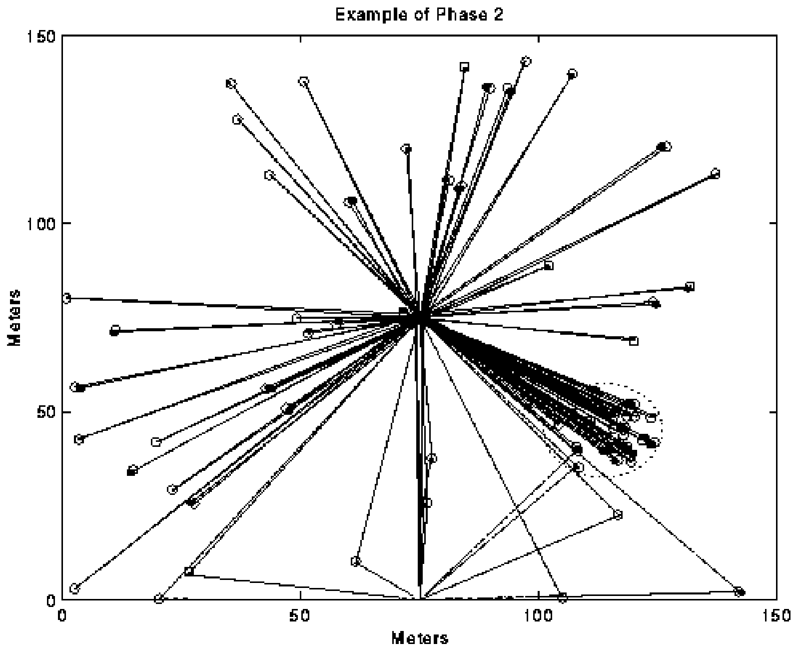


Figure 2.3 -3. Example of BUGS path for the Phase II

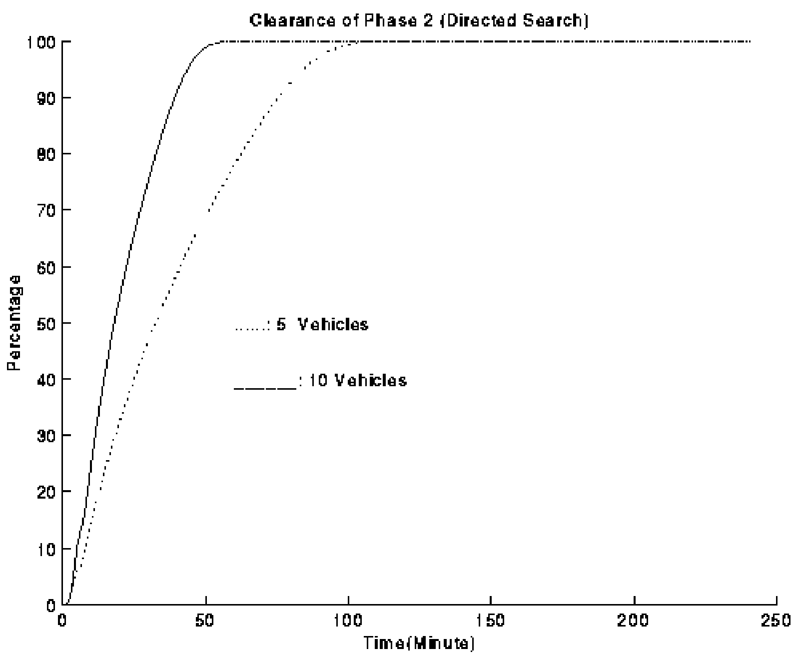


Figure 2.3-4. Clearance rate for BUGS for the Phase II

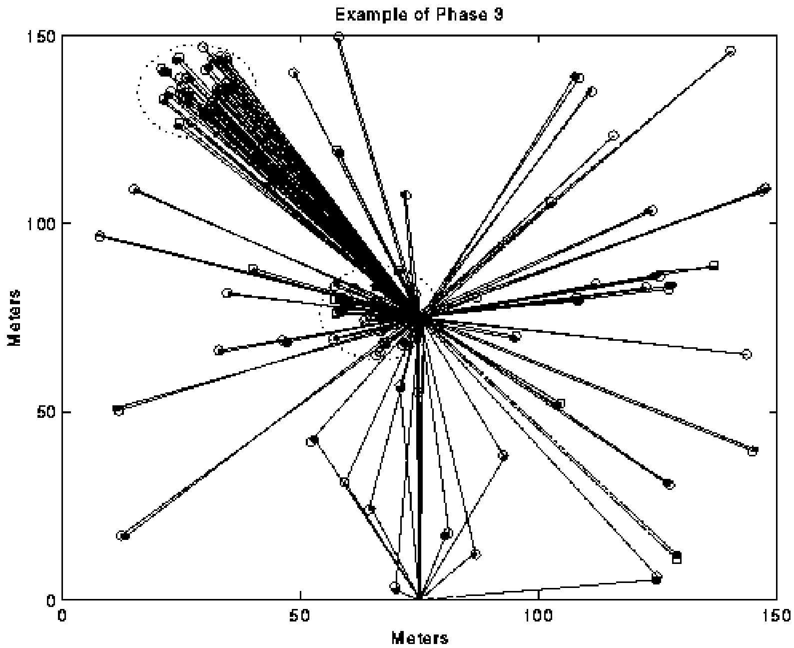


Figure 2.3-5. Example of BUGS path for the Phase III

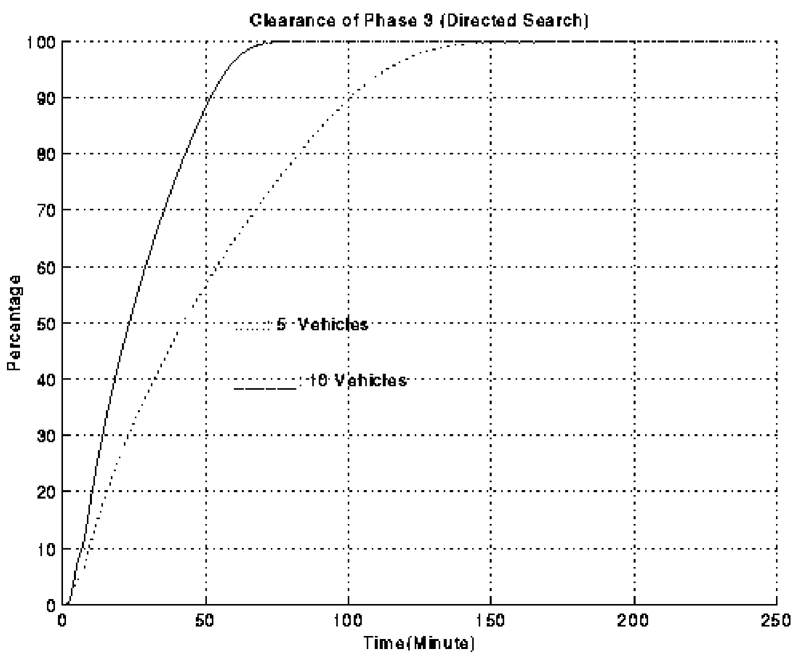


Figure 2.3-6. Clearance rate for BUGS for the Phase III.

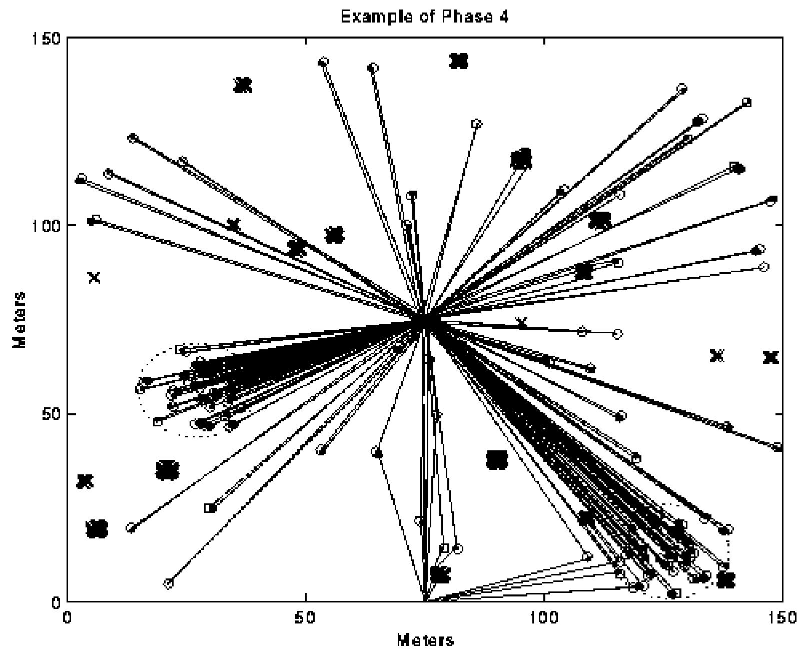


Figure 2.3-7. Example of BUGS path for the Phase IV

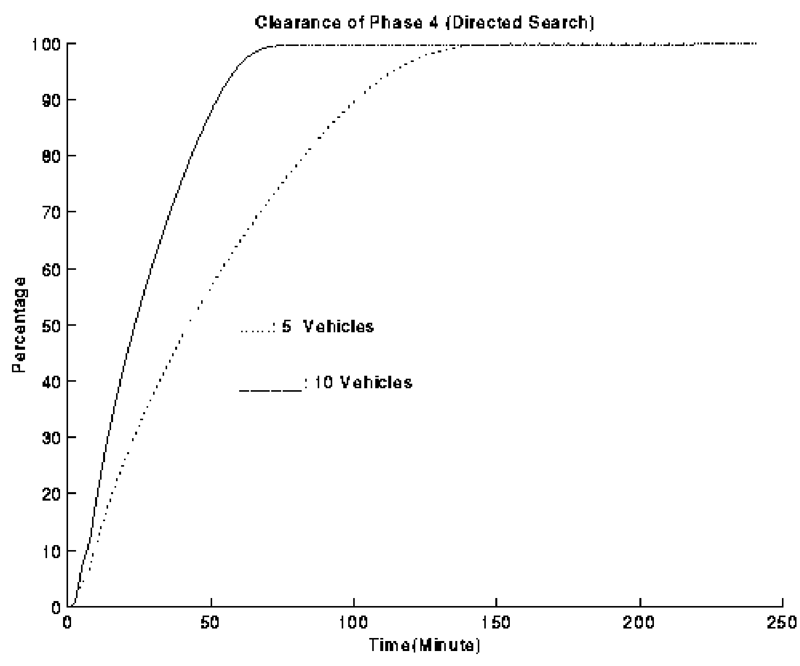


Figure 2.3-8. Clearance rate for BUGS for the Phase IV

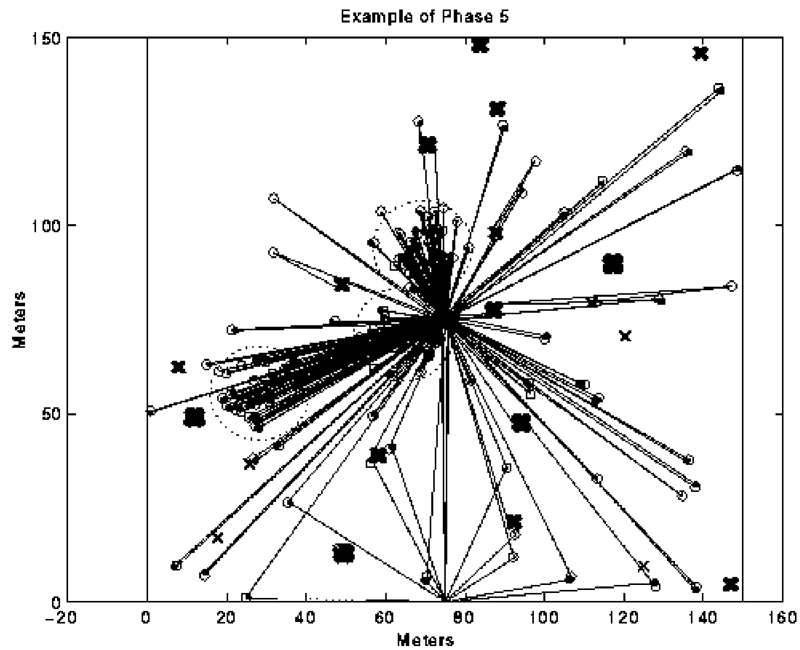


Figure 2.3-9. Example of BUGS path for the Phase V

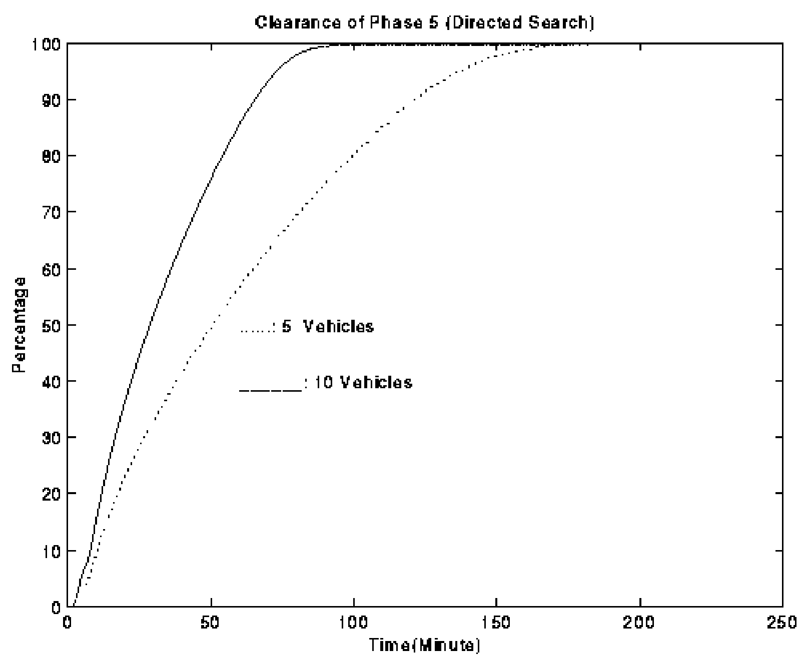


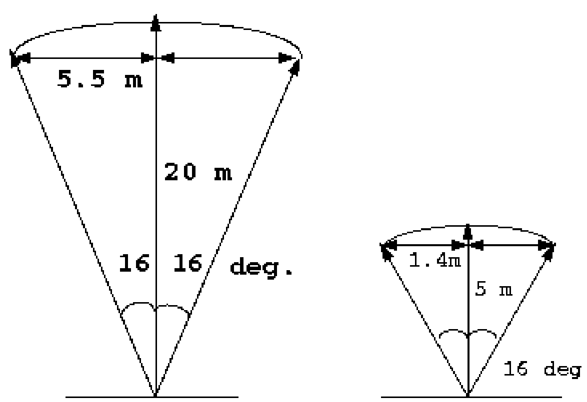
Figure 2.3-10. Clearance rate for BUGS for the Phase V.

Table I Summary of Shared Target List Performance

Scenario	Time for 5 BUGs	Time for 10 BUGs
Phase I	50	30
Phase II	100	55
phase II	140	60
Phase IV	140	60
Phase V	160	80

3. USE OF AUTO-RECORM

This work describes a simulation for autonomous navigation by an Auto-RECORM mobile vehicle in an unknown domain, This simulation based on detecting and classifying all UXOs in a given domain by an Auto-RECORM equipped a fixed camera device. Figure 3.1 shows the range of the camera. The camera has 20 *meter* depth of field with 32 degree field of view while detecting target and 5 meter depth of field while detecting. The system is simulated to provide intelligent autonomous navigation by an Auto-RECORM in an unknown field. By the term *intelligent*, we mean that Auto-RECORM is designed to plan and execute task based on a model of the current state of the external environment.



(a) (b)

Figure 3.1 Camera range (a) detecting range (b) Classifying range

The navigation system of the Auto-RECORM is based on the computational framework shown in Figure 3.2. The Task of the navigation system is to plan a path to a preplanned goal and to execute this plan, modifying it as necessary to avoid UXOs and obstacles. The path planning is divided into global path planning to detecting the targets and local path planning to classifying the targets which is detected and to avoid obstacles.

The global path planning requires a preplanned search pattern (spiral search, lawn mow search, random search etc.) in the given search field which may be somewhat

simplified description of the real world. This global model must provide the planning algorithm with a network of landmark points. We call it global way point(GWP). Auto-RECORM starts a search with global path plan and starts to move to a GWP at speed of 1.0 *mph* with the navigational accuracy of 5 *m*.

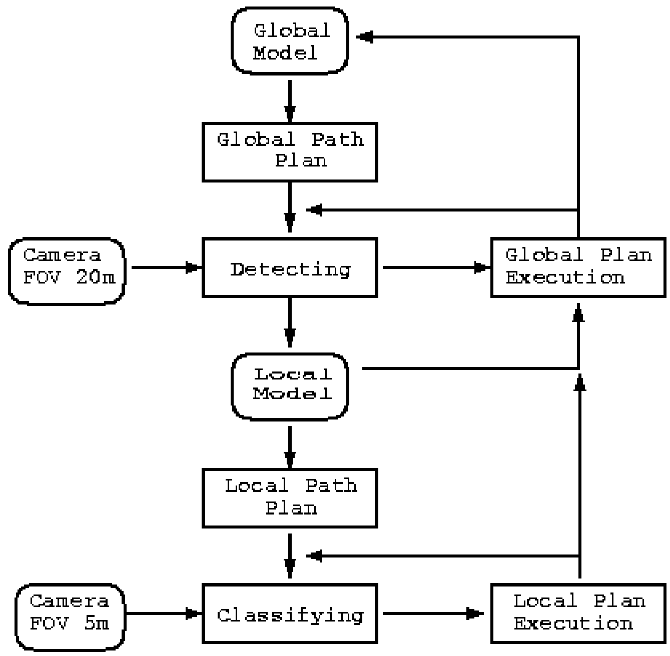


Figure 3.2 Framework for Auto-RECORM Navigation system

There are several ways of performing an exhaustive search. Amongst these are the back and forth or "raster scan" method, the "spiral-in" method, and the "spiral-out " method. Given the assumption that the target is stationary and equally likely distributed anywhere, all methods are equivalent. However, it can be said that the spiral-out method is advantageous if the target is at the center of the spiral than in other places.

3.1 Using Global Spiral Paths

The Global Spiral Path algorithm is as follows: As shown in Figure 3.1-1, Starting at the starting position, the vehicle repeats a cycle of moves wherein the vehicle moves north direction until the Global Way Point(GWP) has been encountered, then west direction until encountering a GWP, then south direction until encountering a GWP, then east direction until encountering a GWP, at which position vehicle direction is redirected to the north, and the cycle repeated until whole search area is swept out. The number in Figure 3.1-1 represents the ratio of the distance of each direction. The Global spiral path machine is shown in Figure 3.1-2.

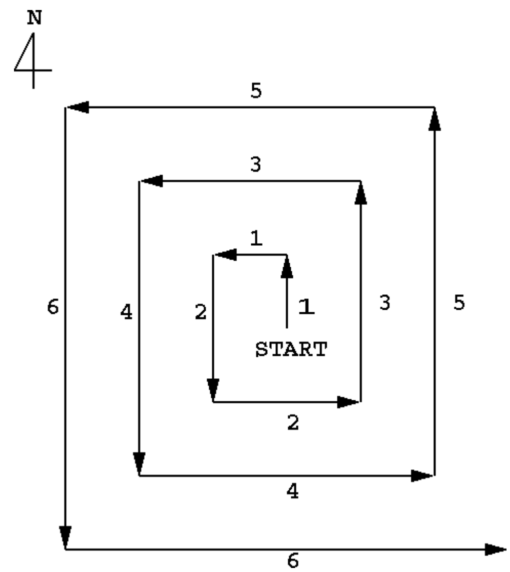


Figure 3.1-1 Global Spiral Path: Arrow points represent the Global Way Points

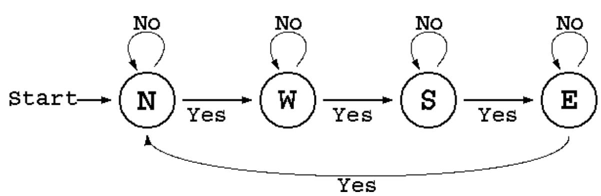
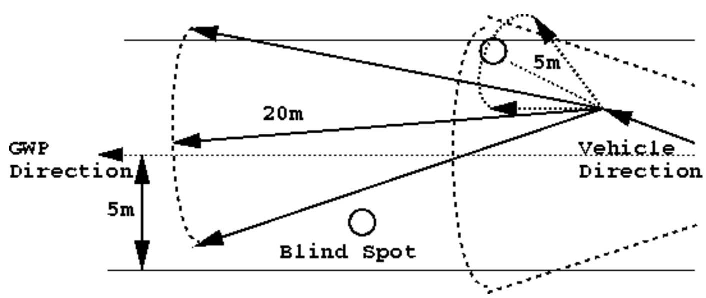
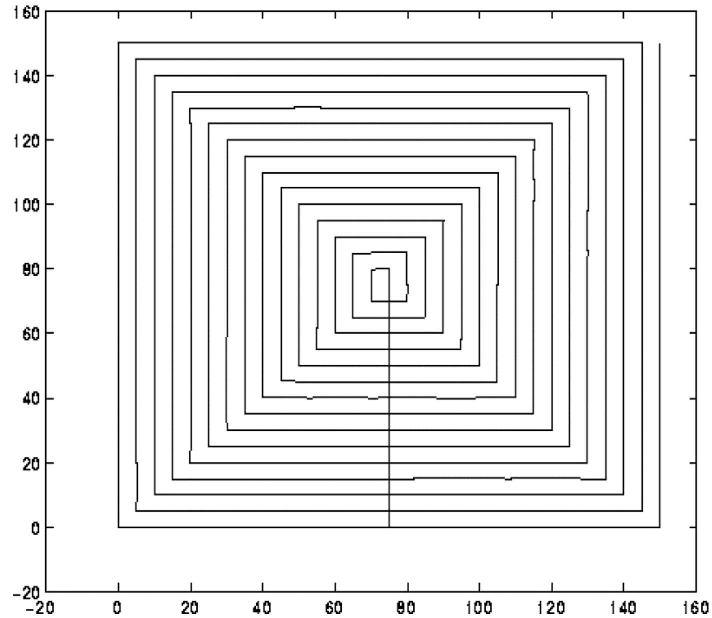
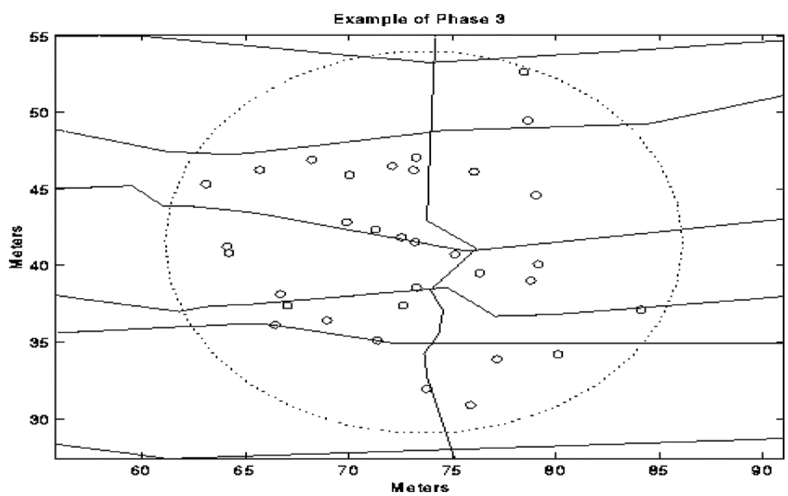


Figure 3.1.2 State machine calculating global way point**.**

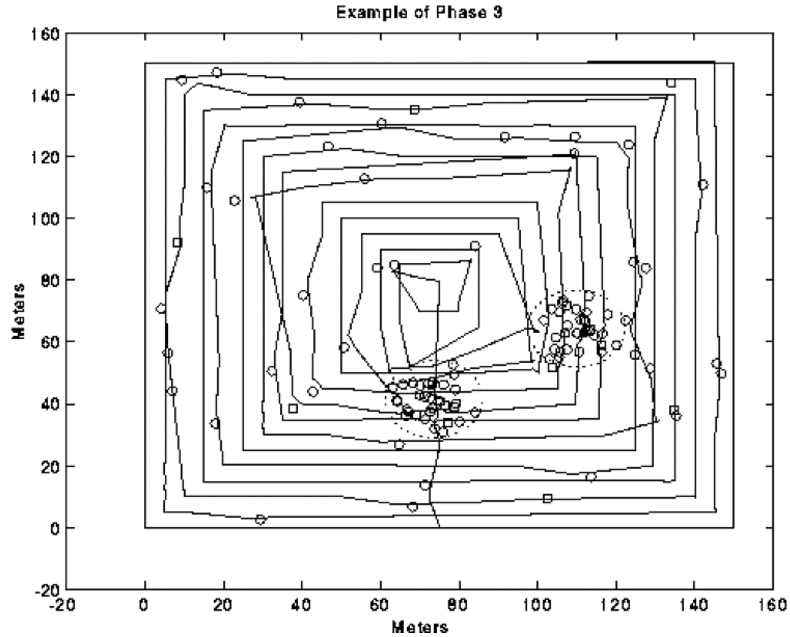


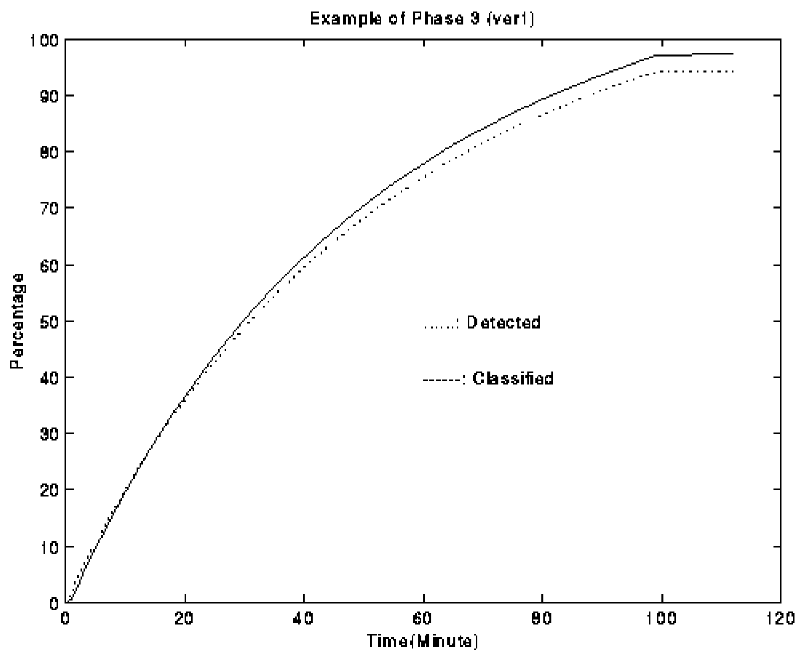


a) Global Waypoints and Path plots



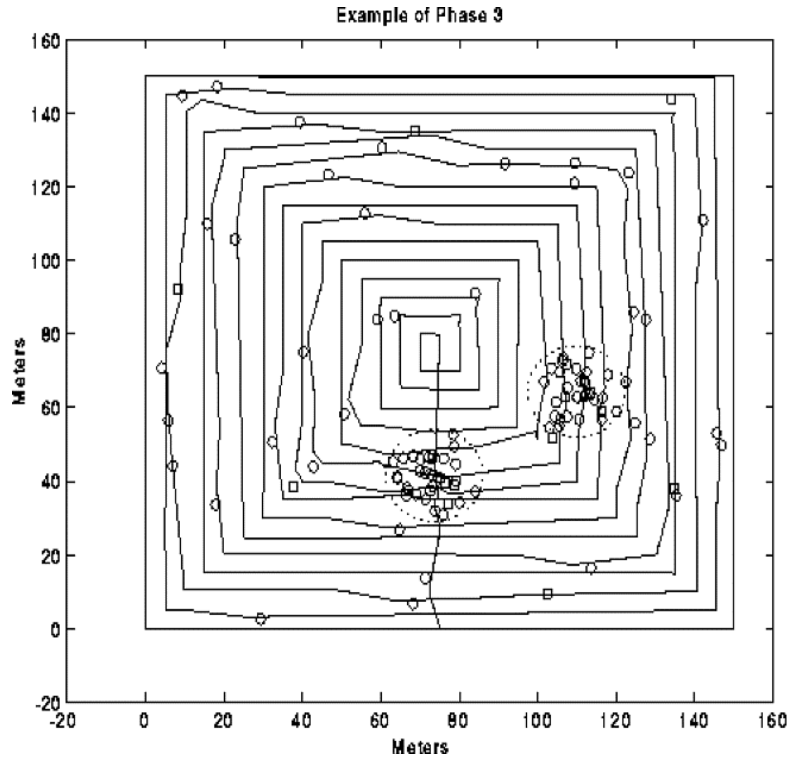
b) Targets Identified Using Auto-Recorm Alone Going Through a Clusters

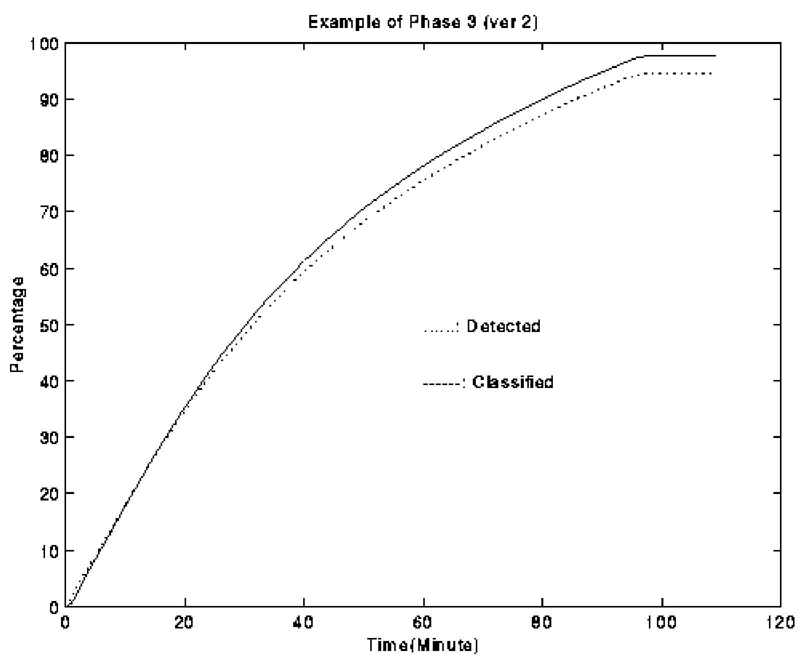


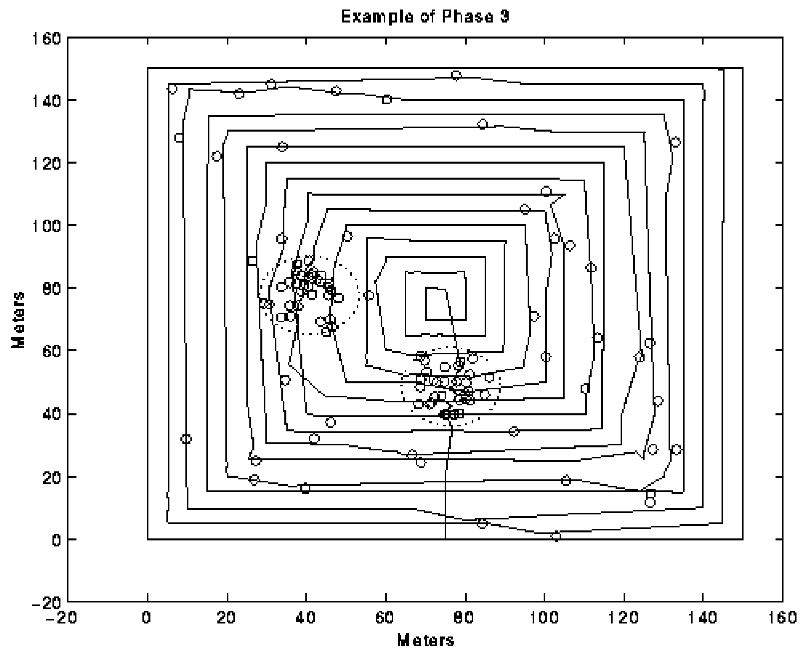


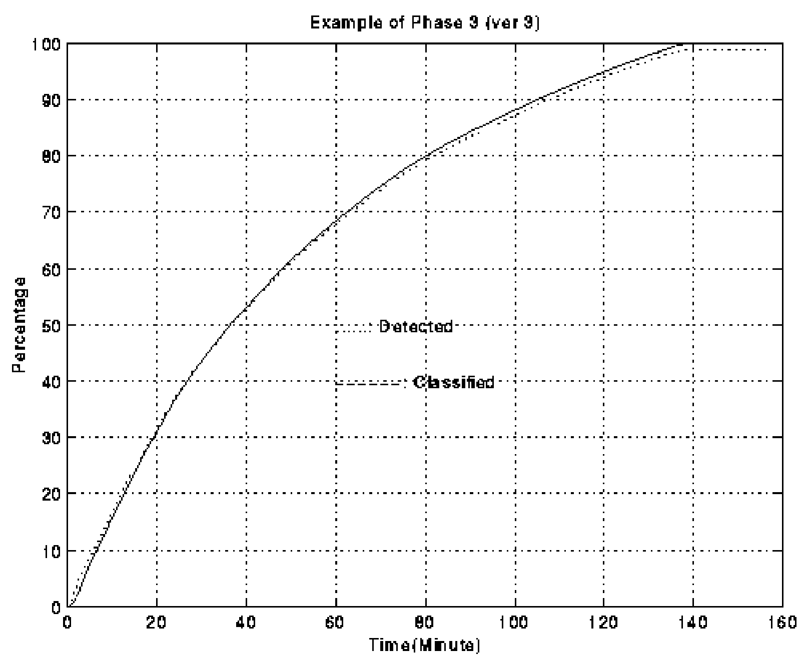
Phase 3 Detection / Classification Performance

c) Algorithms For Regaining GP While Identifying Targets









2.2 Lawnmower Paths

d) AR 'circling' Clusters (Detection only - no Classification

4 DYNAMIC ZONE ALLOCATION (DZA)

A search technique, which is called Dynamic Zone Allocation (DZA), is described for an autonomous mobile robot operating in unknown and unstructured environments. DZA is a search technique to efficiently find targets that may be encountered in clusters within a larger area. An advantage of DZA is that a maximum number of targets can be found in a limited amount of time. The robots disperse, and

randomly search for targets. As one target is found, this is assumed to be part of cluster, and the location is designated as the center of a DZ. Other available searchers are summoned to the newly defined DZ to perform random searches within the zone. As additional target is found within the DZ, the location is designated as the center of a new DZ. After some predetermined time (a time out). If no targets are found within the DZ, the searchers summoned to the newly defined DZ to perform random searches within the zone. If no DZ is available, the searchers are dispersed again to randomly search the entire operating area. The major module of this system is described. Results from actual simulation runs are presented.

Conceptual Processing Levels For a Vehicle

The Dynamic Zone Allocation (DZA) search system described in this paper is part of a wider investigation into issues related to the development of a software architecture for an autonomous mobile vehicle. In this section, we briefly outline a conceptual processing levels into which the various problem-solving activities of a vehicle software architecture can be classified. The processing levels include the random search within the entire operating area, navigation to DZ, random search within the local search area, navigation to Disposal Place, and supervisor levels, and briefly described below.

4.1 Random Search Within The Entire Operating Area.

Figure 1 shows the operation state machine for the random search within the entire operating area. The vehicles travel on randomly selected headings in the predominant direction, and change to new random headings every 5 sec. If an UXO is found, BUG picks up the UXO and reports the location of the target to supervisor, which is the center of a new DZ. And the vehicle navigates to Disposal place, which is located in the middle of the search field. During the random search, vehicle checks the message from supervisor. If there is an assigned a new task from supervisor, the BUG immediately execute the new task. If there is no message from supervisor, then continue the random searching within the entire field by changing its heading randomly every 5 sec.

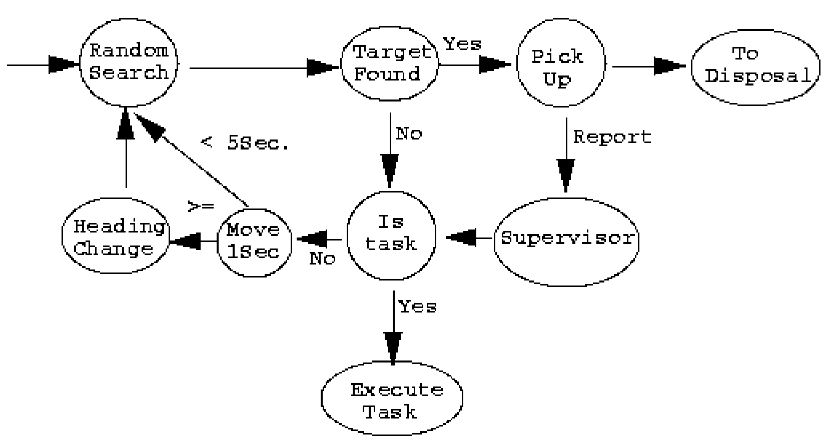


Figure 4.1 State Machine For The Random Search Within The Entire Area.

4.2 Navigation To The Goal Of The Task

If a vehicle is assigned to a task from supervisor, and then vehicle first travels to the goal of the task to execute the task that is random search in DZ area. Figure 2 shows the operation state machine for the navigation to the goal of the task. If the BUG is found a target during the navigation to the goal, then picks up that UXO, and reports to the supervisor the location of the target. This location is the center of new DZ. And the vehicle navigates to Disposal place to drop off it. Otherwise, it navigates to the goal using its GPS unit and the compass. With error on both the GPS and the compass, it corrects its heading every 5 sec. until it is placed in the vicinity of the goal. It then performs random search of the surrounding area (Execute the Task).

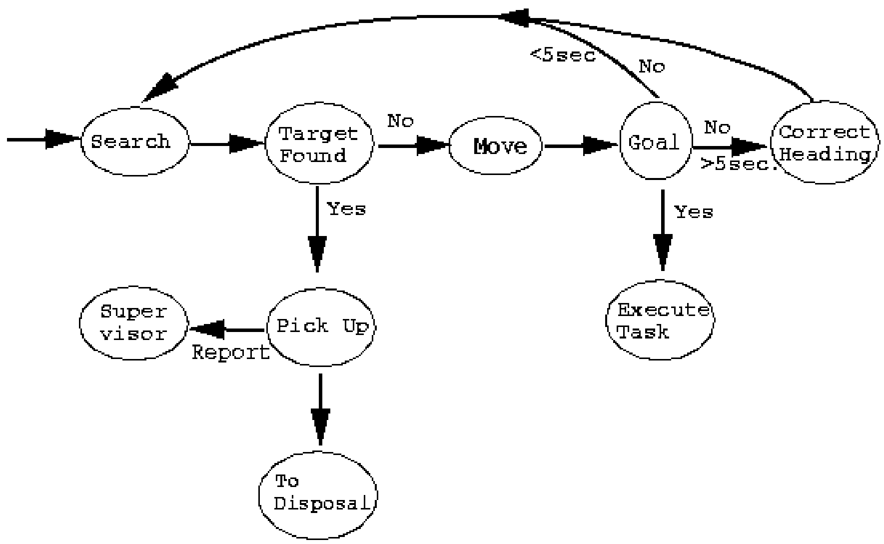


Figure 4.2. State Machine for Navigation to the Goal of the Task

4.3 Random Search Within Local Search Area.

As a vehicle arrived in a vicinity of the goal of task, vehicle starts random search within the DZ area. If the vehicle does not find it within 150 sec. vehicle report it to supervisor and gets new task from supervisor and execute the new task. If no task is available, then vehicle disperses and starts random search within the entire area. If the searcher finds a target, reports to supervisor, picks up the target and carries away to the disposal place. Figure 3 shows the operation state machine.

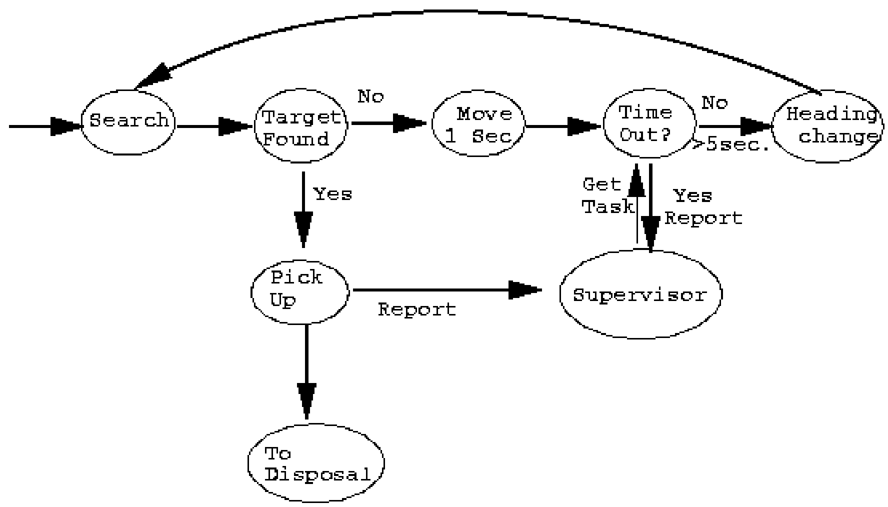


Figure 4.3. State Machine for Searching in the DZ Area

4.4 Navigation to the Disposal Area.

If any UXO lies within the detection radius of a vehicle, that UXO is assumed to be acquired by that particular vehicle. Following that action, the vehicle is assumed to change its heading to disposal site. The vehicle then navigates to the drop-off area, avoiding both obstacles and other not yet acquired targets while enroute to the disposal site. PUCA operation is shown in Figure 4. During the navigation to disposal place, vehicle is searching target continuously. If a target is found, vehicle reports the location of the target to supervisor and navigates to the drop-off area, avoiding the target. When the vehicle enters the drop-off area, it drops off its UXO and turn around. And the vehicle reports the current situation to supervisor to get a new task. If a new task is assigned, then vehicle navigates to the goal of the new task. Otherwise, vehicle disperses to perform random search within the entire search area.

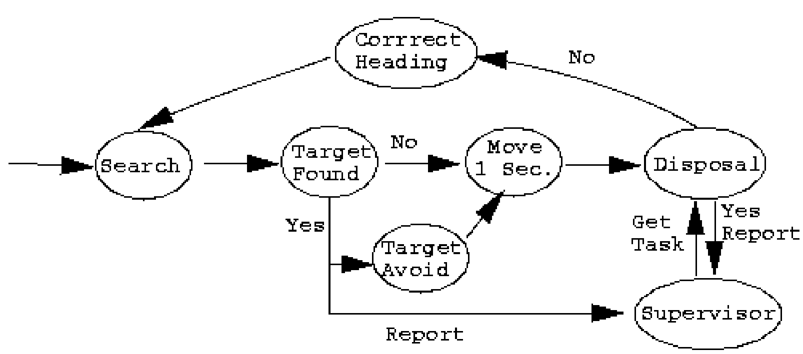


Figure 4.4. State Machine for Navigation to Disposal Place

4.5 Supervisor

When a vehicle found a target, it reports target position to supervisor with a message. Table 1 shows the message to supervisor from a vehicle based on vehicle status

and event (Target Found/ Target not Found). During the navigation to Disposal Place, if a vehicle found a target, then it sends a message –1, target ID, 1. It means that the vehicle has no previously assigned task and there exists a target within DZ1 (one meter radius circle area) and the location of the target ID is the center of DZ1. Because it cannot pick up and carry away the target. If a vehicle found a target during random search within the entire search area (150 m x 150 m), a message to a supervisor is –1, target ID, 5. It means that it found a target and picked up and carrying away the target, and ready to navigate to Disposal Place. And the location of the target is the center of the DZ5 (5 meter radius area). During random search within DZ1 or DZ5, if vehicle found a target, then message to supervisor is Target ID, Target ID, 5. The first Target ID represents the previously assigned the center of search area, and the second Target ID represents the center of the new DZ5. If the vehicle fails to find a target for a given amount of time within the search area DZ1 or DZ5, the message will be Target ID, -1, -1.

Table 2. Communication to Supervisor based on vehicle status and event (Target Found/ Target not Found).

Vehicle Task	Target Found			Target Not Found		
	Previous	**Current**	**DZ**	**Previous**	**Current**	**DZ**
Navigation to Disposal Place	-1	Target ID	1	X	x	x
Random Search in Entire Area	-1	Target ID	5	X	x	x
Random Search in DZ1	Target ID	Target ID	5	Target ID	-1	-1
Random Search in DZ5	Target ID	Target ID	5	Target ID	-1	-1
Navigation to DZ Area	Target ID	Target ID	5	X	x	x
Navigation to Home	-1	Target ID	5	X	x	x

Whenever a message arrives, supervisor analyzes the message. If the message is for the new task, decide the priority of the task, put in the task array corresponding its priority. And supervisor makes a decision to assign a task to a available vehicle. There are *n* vehicles to be assigned to *m* tasks. The cost of i-th vehicle to the j-th task is C_{ij} . We are to develop an algorithm which assigns vehicles to tasks and the same time minimize the total cost of the assignment. This process can be viewed in terms of a cost function that includes such factors as the navigation time of the path or trajectory, and local search time S_t. An outline of the detailed steps involved is shown below.

Algorithm (Assignment problem)

1. Calculate cost C_{ij} in Table 2 navigation time from the current position of a vehicle to the center of tasks, where

$C_{ij} = \infty$ if vehicle is on navigation to Disposal Place,
= remaining search time if vehicle is on searching within DZ1/DZ5
= search time S_t plus navigation time from the current position of a vehicle to the center of tasks otherwise.

Table 2. Array of the costs.

	Task 1	**Task 2**	**.**	**Task m**
Vehicle 1	C_{11}	C_{12}	.	C_{1m}
Vehicle 2	C_{21}	C_{22}	.	C_{2m}
.		.	.	.
Vehicle n	C_{nm}	C_{n2}	.	C_{nm}

2. For j = 1, m

$$C_{ij} = C_{ij} \text{ if } C_{ij} - (\min_i C_{ij}) - S_t <= \rho \text{ where } \rho \text{ is a threshold.}$$
$$= \infty \text{ otherwise.}$$

3. Find j such that $\min_j C_{ij}$.

Why DZ5 is defined?

Assume one cluster, circular shape, with a diameter of 25 meters. The target density within the cluster is 0.0667 per square meter, for approximately 33 targets within the cluster. Assume that targets are uniformly distributed within the cluster. Then Average distance of targets is 4.35 meter.

Proof: Since targets are uniformly distributed within the cluster,

$$A_{cluster} <= n_t \cdot A_{target}$$

Where $A_{cluster}$ is the area of the cluster, n_t is number of the targets, and A_{target} is the area of a target. So

$$A_{cluster} = \pi r_{cluster}^2 <= n_t \cdot A_{target} = n_t (\pi r_{target}^2)$$

$$r_{target} >= \sqrt{\frac{\pi \cdot (12.5)^2}{\pi \cdot n_t}} = \sqrt{\frac{12.5^2}{33}} = 2.1760$$

What is the average Search time?

Assume that targets are uniformly distributed within the cluster, then average search time to find a target within the cluster for the 90 % clearance rate is approximately 200 second.

Proof: The expected clearance rate for the random search as the function of the time is given by

$$\frac{q(t)}{n_0} = 1 - e^{-\alpha t}$$

where $\alpha = U(2r)pN/A$ *, U is the vehicle speed, r is the sensor radius of detection, p is the sensor's probability of detection when a UXO is within the detection radius, N is the number of BUGs, A is the area to be searched, and* n_0 *is the initial number of UXO. The 90% clearance rate becomes*

$$0.9 = 1 - e^{-\alpha t}$$

$$t = -\frac{\log(0.1)}{-\alpha}$$

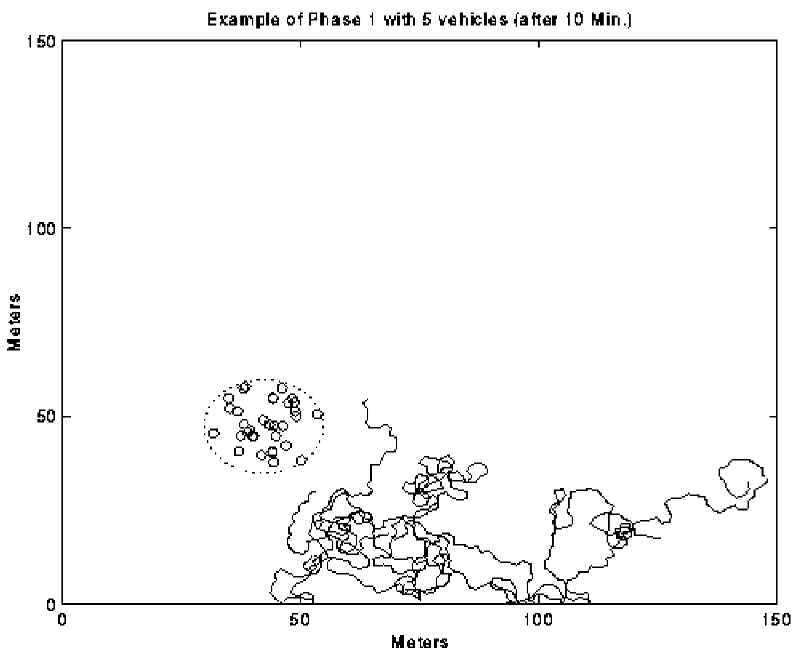
where $\alpha = \frac{(0.4572)(2\times 0.1905)(1.0)(1)}{\pi(12.5)^2}$.

So, average elapsed time for one BUG to find a target within the cluster becomes

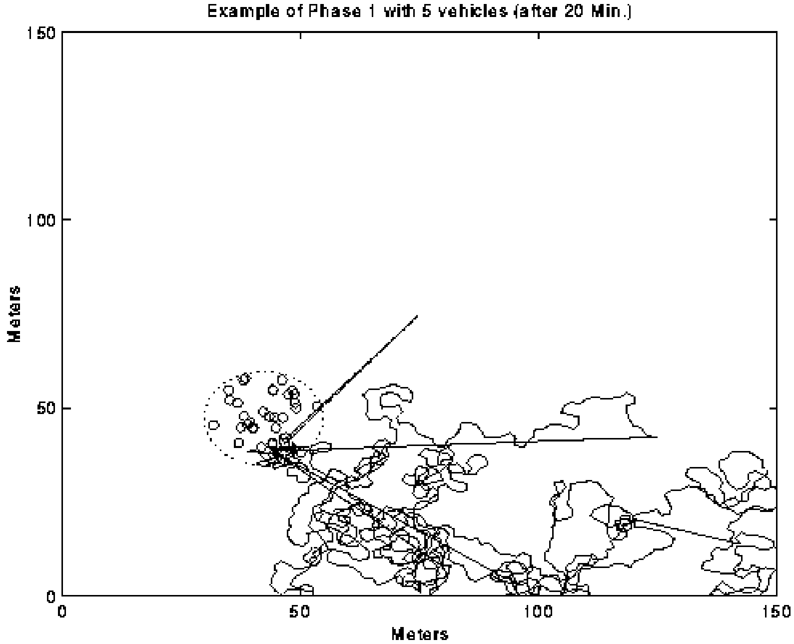
$$\frac{t}{n_0} = \frac{\log(0.1)}{-n_0}\alpha \approx 200 \text{ sec.}$$

4.6 Priority Task Classes.

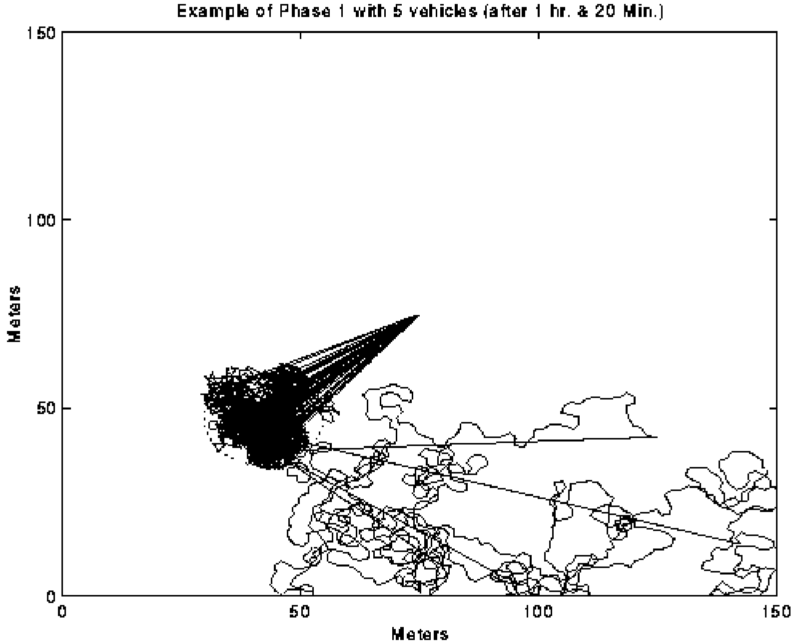
In our algorithm, there is three priority classes. The priority class 1 is highest priority class and priority 3 is lowest priority class. If a target was found by a vehicle during navigation to Disposal Place, randomly searching within entire search area, and navigation to DZ1/DZ5 area, defined task is in the priority 3 class. If a target was found within DZ5, the new task priority is defined as a higher priority than the priority of the previously task. In Priority Task Solution the tasks fall into different priority classes. We assume that no task fall into different priority classes. In this case we first apply the assignment algorithm to the highest priority class and then if there is a free vehicle, then apply the assignment algorithm to the next priority class, and so on.

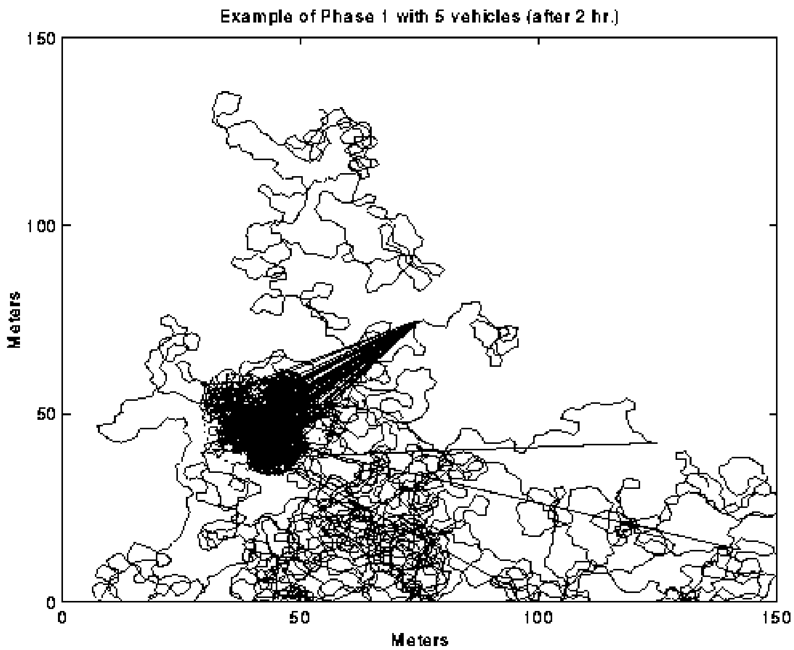


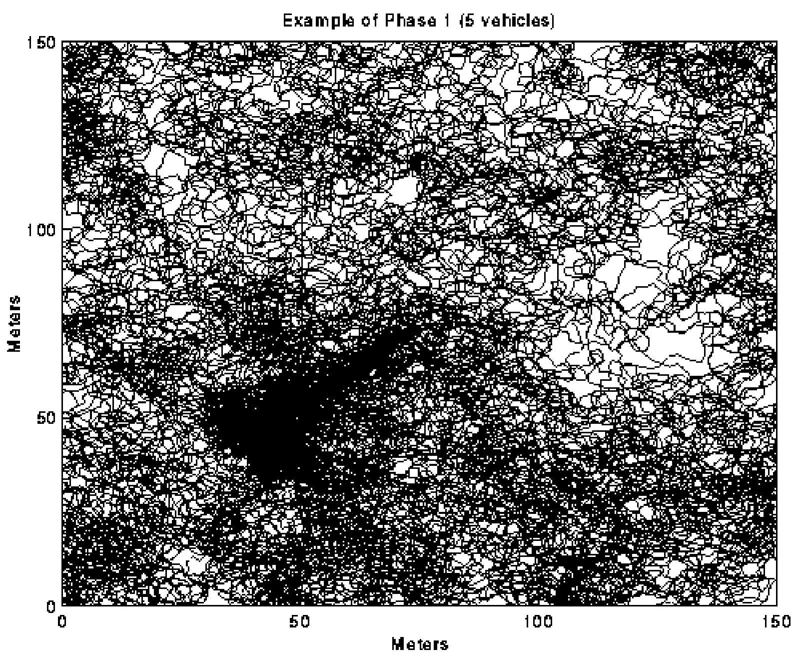
Example of Phase 1 with 5 vehicles (after 20 Min.)

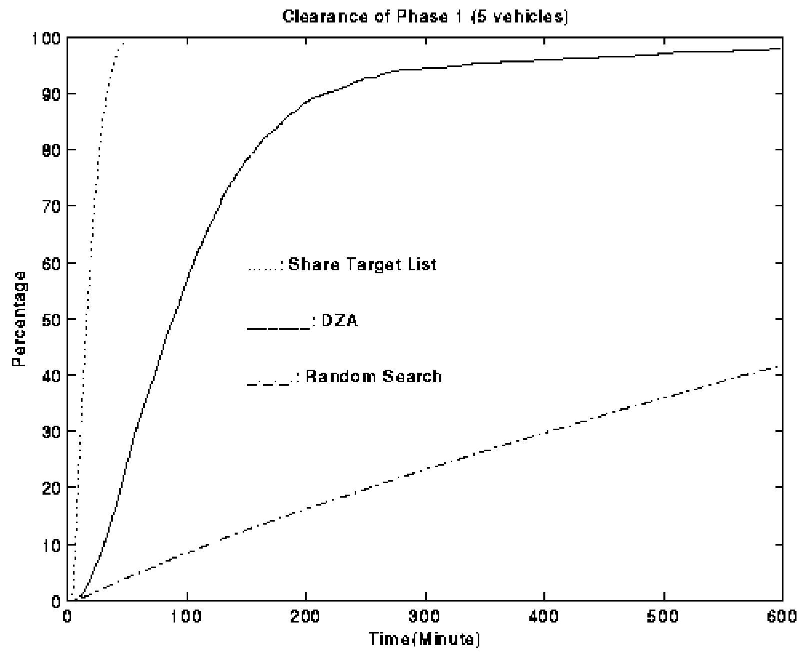


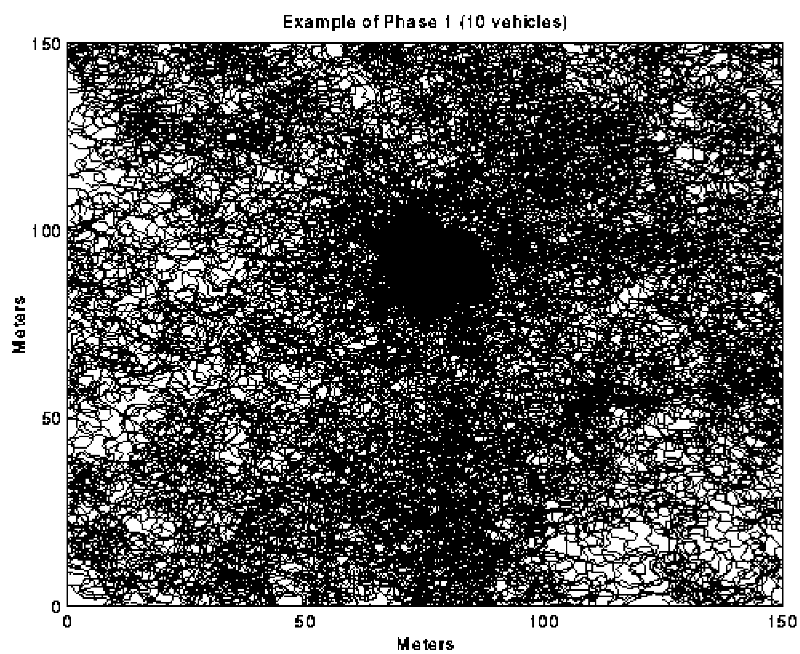
Example of Phase 1 with 5 vehicles (after 1 hr. & 20 Min.)

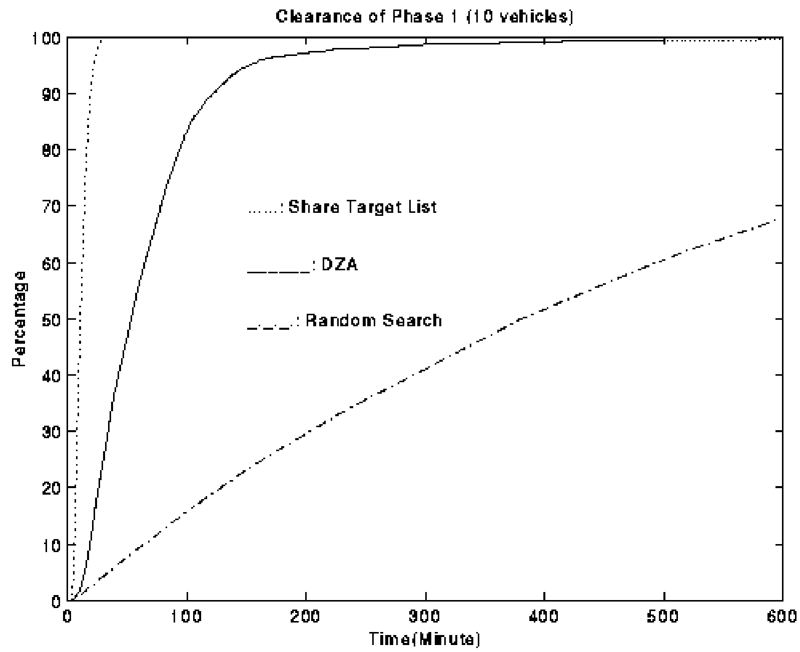



Example of Phase 1 with 5 vehicles (after 2 hr.)
Meters
Meters
0
50
100
150
0
50
100
150


Example of Phase 1 (5 vehicles)
Meters
Meters
0
50
100
150
0
50
100
150


Clearance of Phase 1 (5 vehicles)
Percentage
Time(Minute)
......: Share Target List
______: DZA
_._._.: Random Search
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600


Example of Phase 1 (10 vehicles)
Meters
Meters
0
50
100
150
0
50
100
150


Clearance of Phase 1 (10 vehicles)
Percentage
Time(Minute)
......: Share Target List
______: DZA
_._._: Random Search
0
10
20
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40
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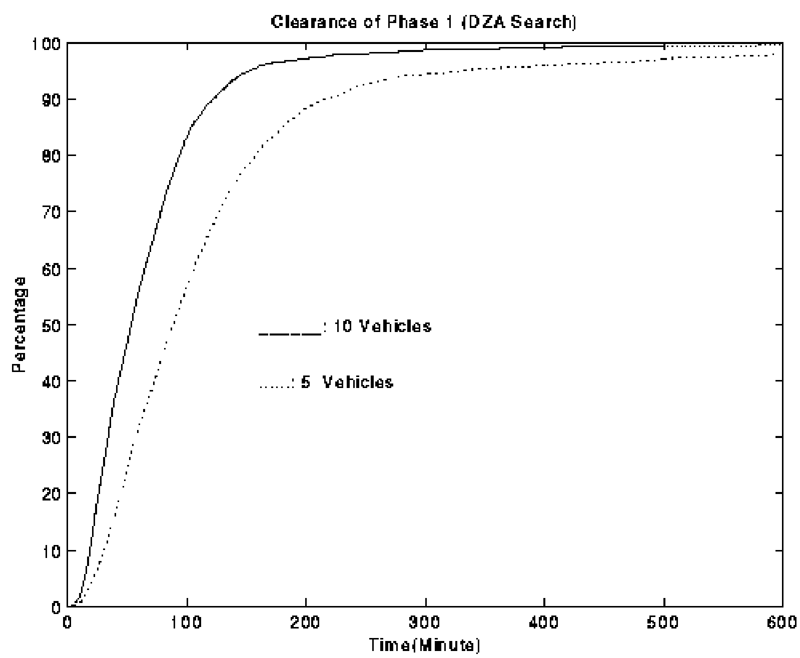
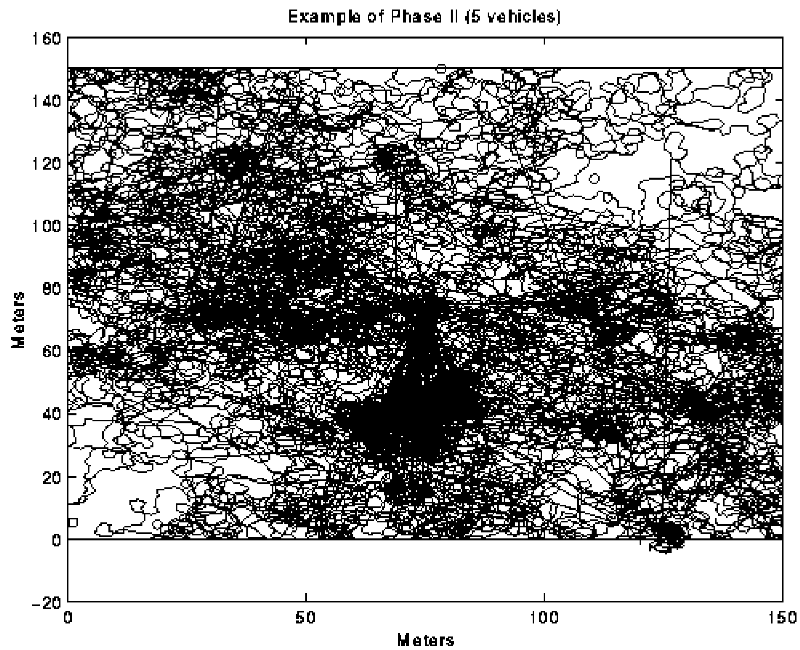
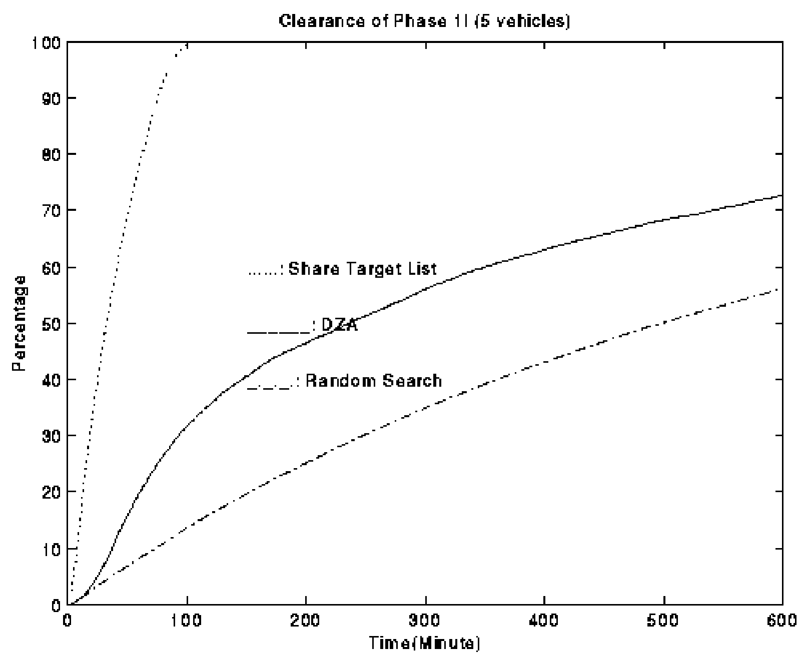
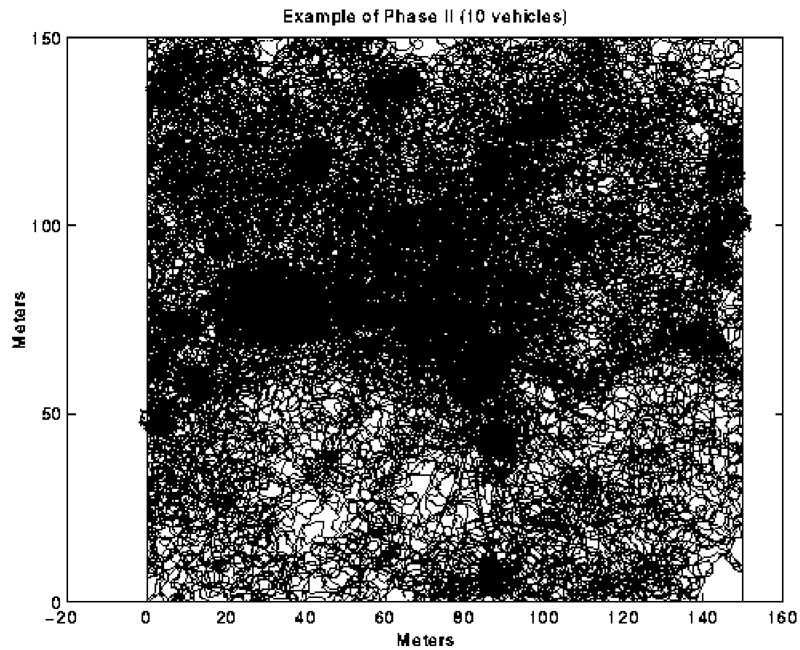
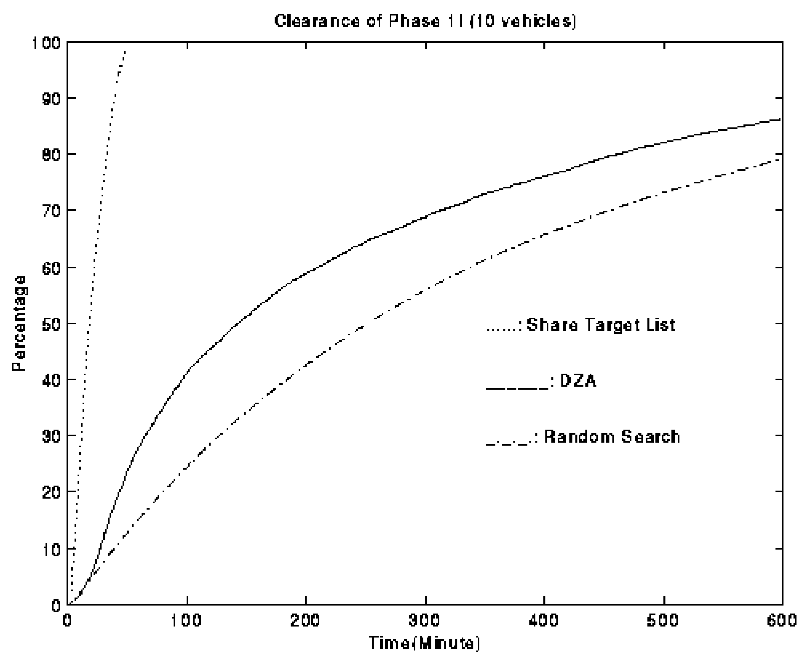
60
70
80
90
100
0
100
200
300
400
500
600

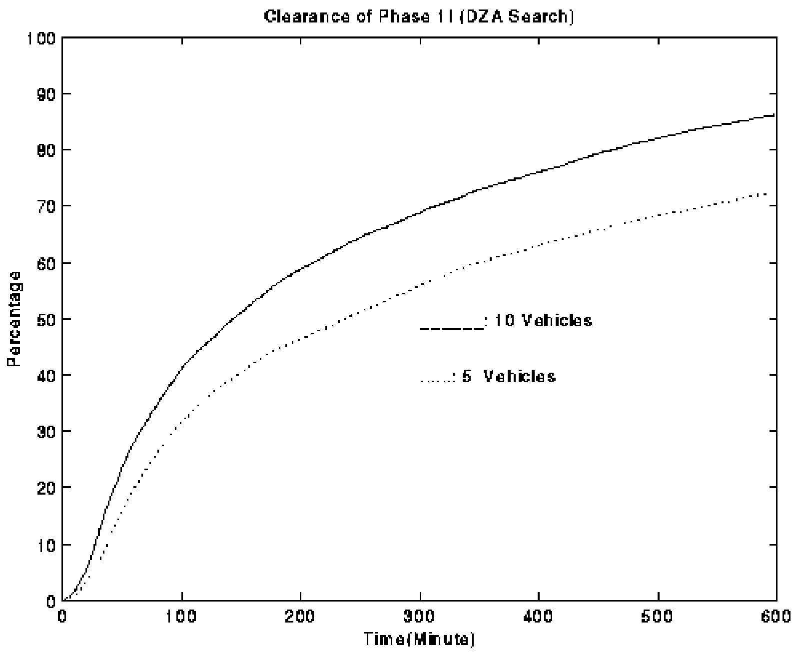

Clearance of Phase 1 (DZA Search)
Percentage
Time(Minute)
______: 10 Vehicles
......: 5 Vehicles
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600

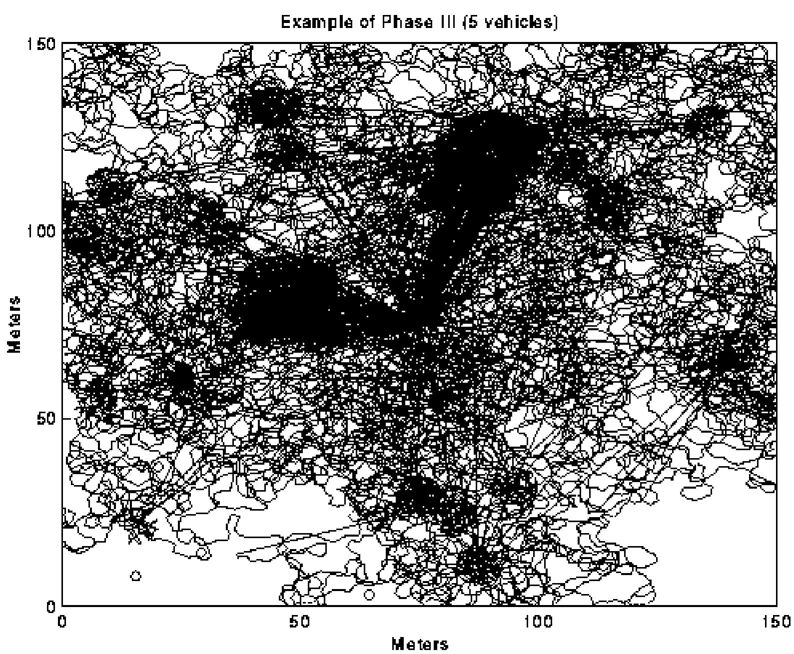

Example of Phase II (5 vehicles)
Meters
Meters
160
140
120
100
80
60
40
20
0
−20
0
50
100
150

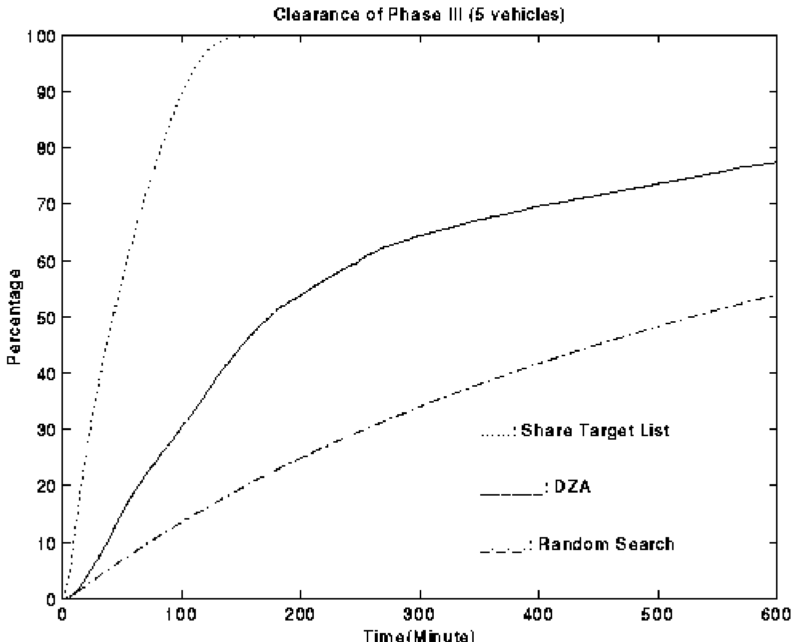

Clearance of Phase II (5 vehicles)
Percentage
Time(Minute)
100
90
80
70
60
50
40
30
20
10
0
0
100
200
300
400
500
600
......: Share Target List
______: DZA
_._._.: Random Search

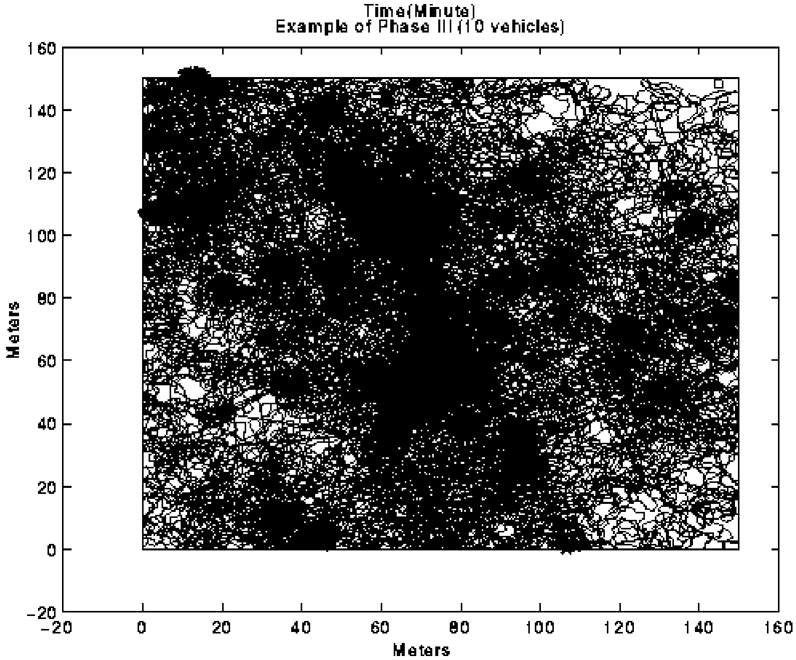

Example of Phase II (10 vehicles)
Meters
Meters

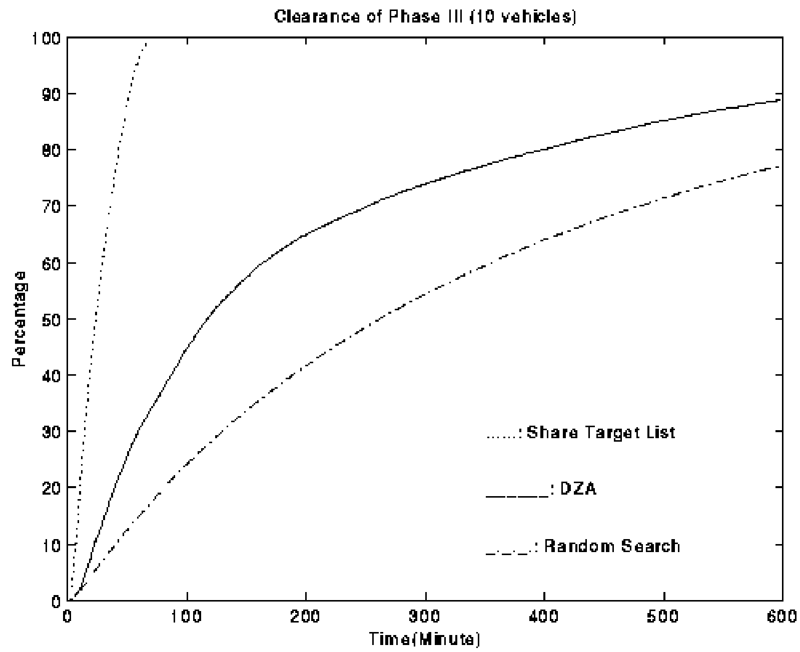

Clearance of Phase II (10 vehicles)
......: Share Target List
______: DZA
_._._.: Random Search
Percentage
Time(Minute)


Clearance of Phase II (DZA Search)
Percentage
Time(Minute)
______: 10 Vehicles
......: 5 Vehicles
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600


Example of Phase III (5 vehicles)
Meters
Meters
0
50
100
150
0
50
100
150


Clearance of Phase III (5 vehicles)
Percentage
Time(Minute)
......: Share Target List
______: DZA
_._._.: Random Search


Example of Phase III (10 vehicles)
Meters
Meters


Clearance of Phase III (10 vehicles)
Percentage
Time(Minute)
......: Share Target List
______: DZA
_._._.: Random Search
0
100
200
300
400
500
600
10
20
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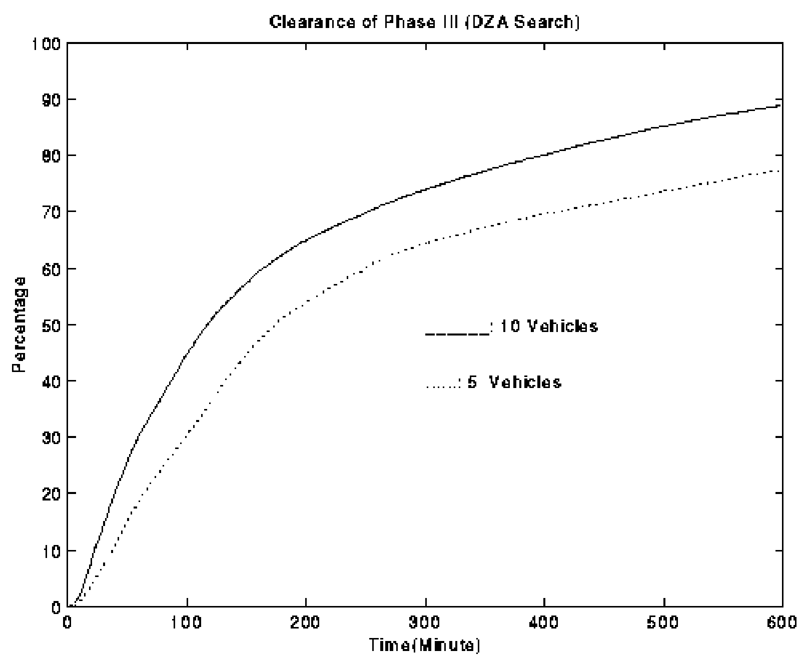
40
50
60
70
80
90
100


Clearance of Phase III (DZA Search)
Percentage
Time(Minute)
______: 10 Vehicles
......: 5 Vehicles
0
100
200
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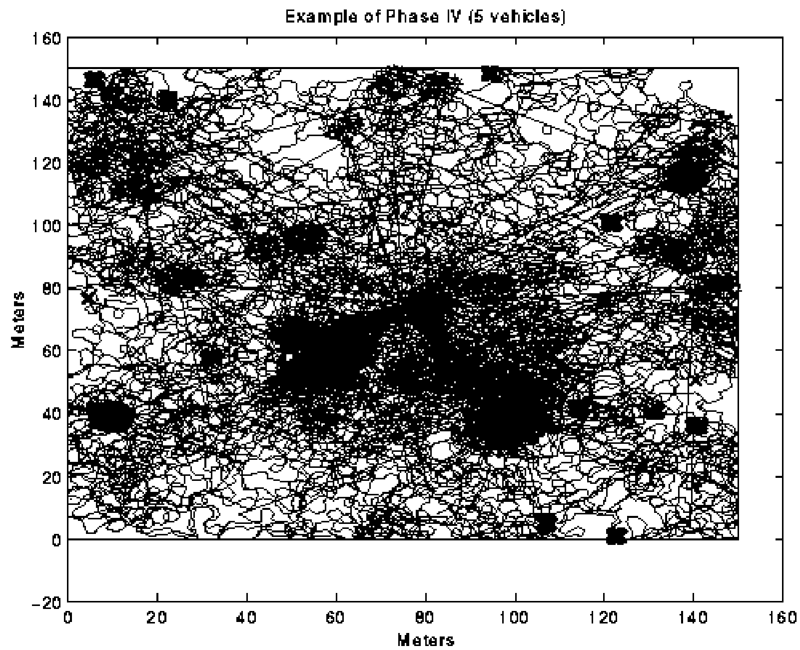
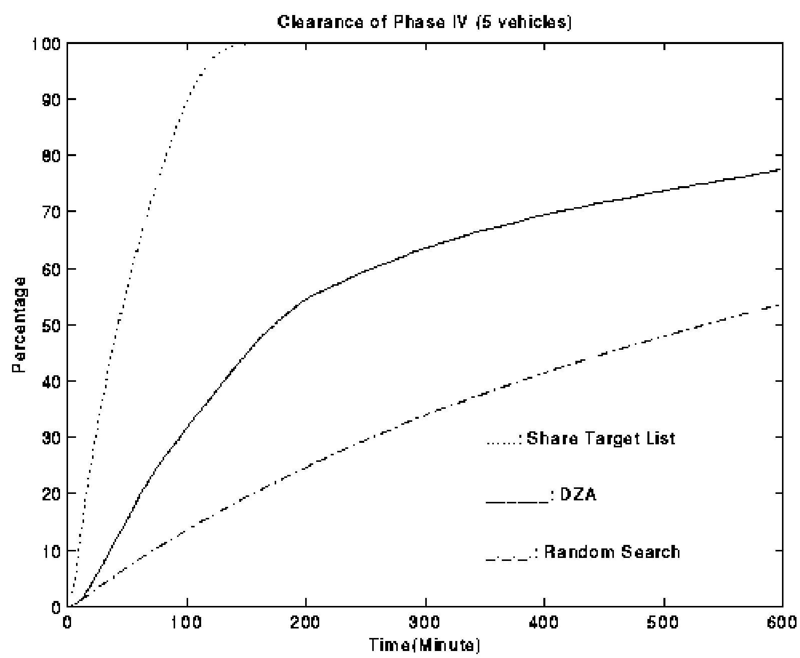
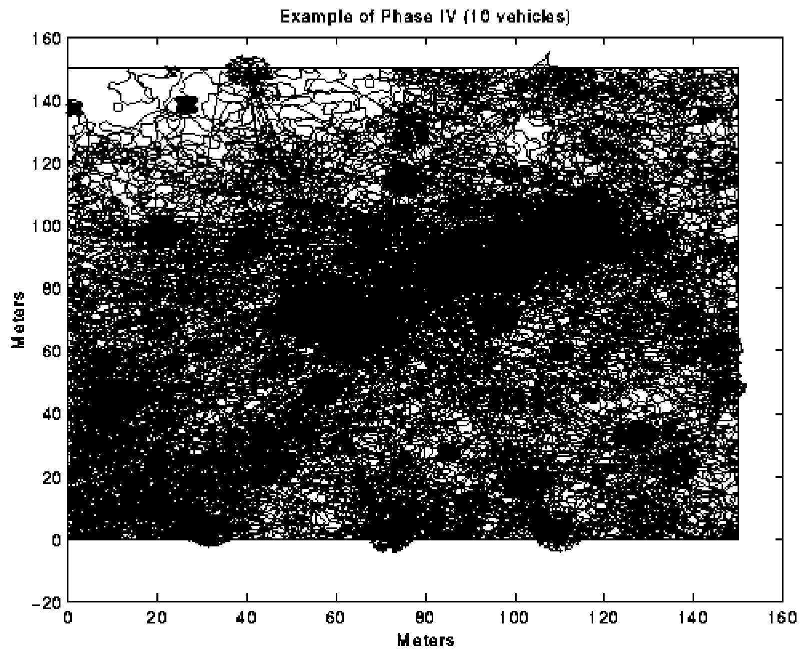
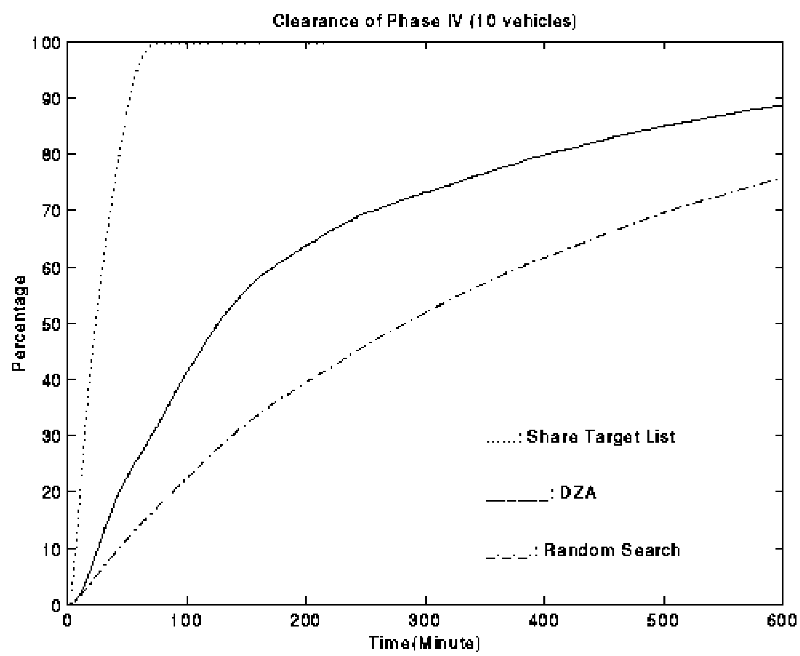


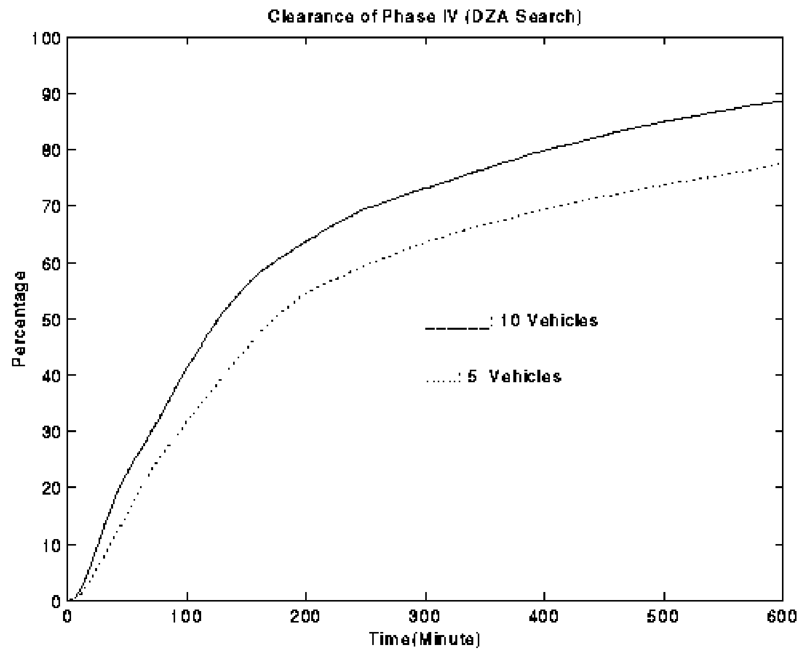
Example of Phase IV (5 vehicles)
Meters
Meters

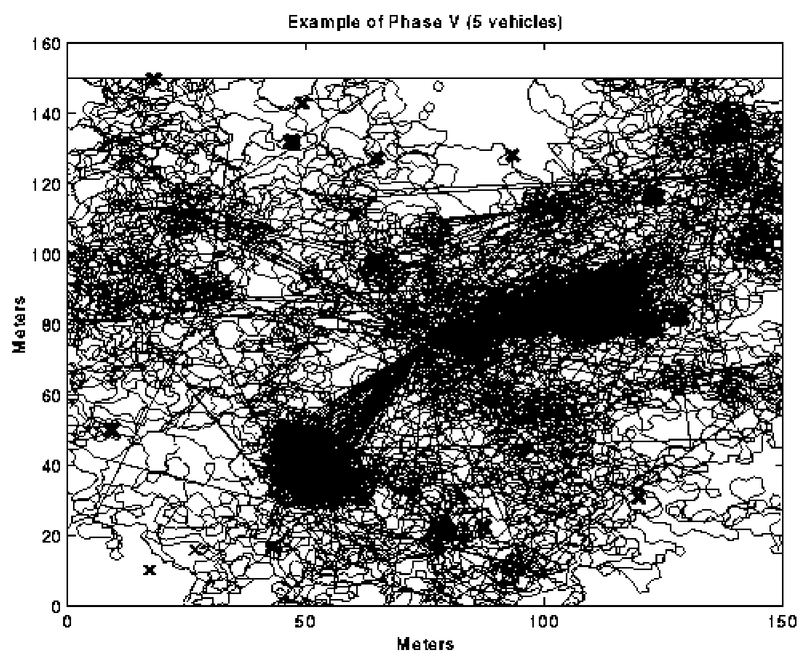


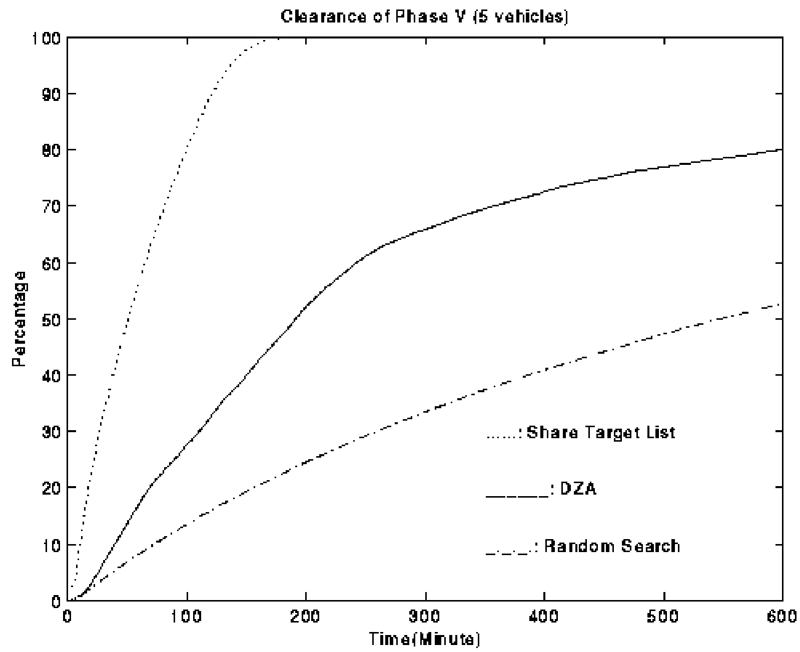
Clearance of Phase IV (5 vehicles)
Percentage
Time(Minute)
......: Share Target List
______: DZA
_._._.: Random Search

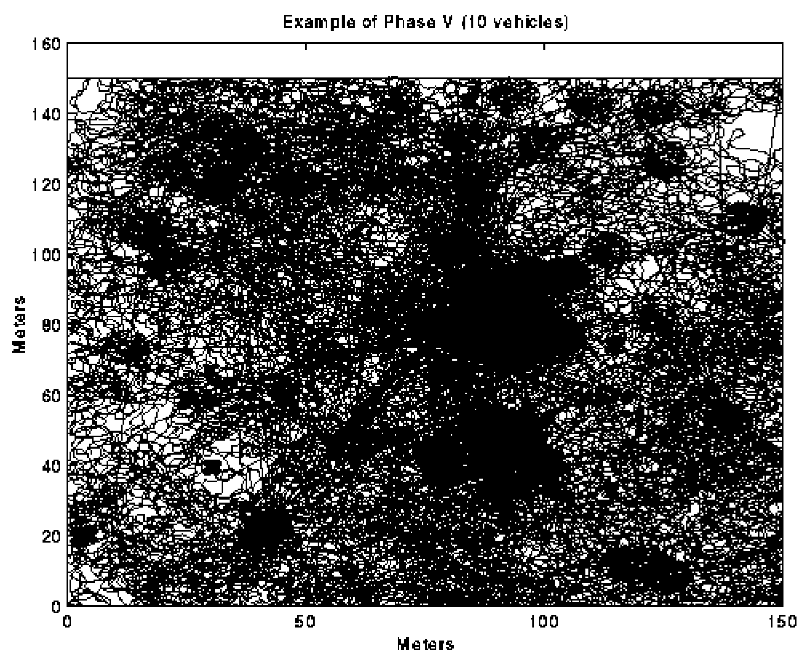

Example of Phase IV (10 vehicles)
Meters
Meters

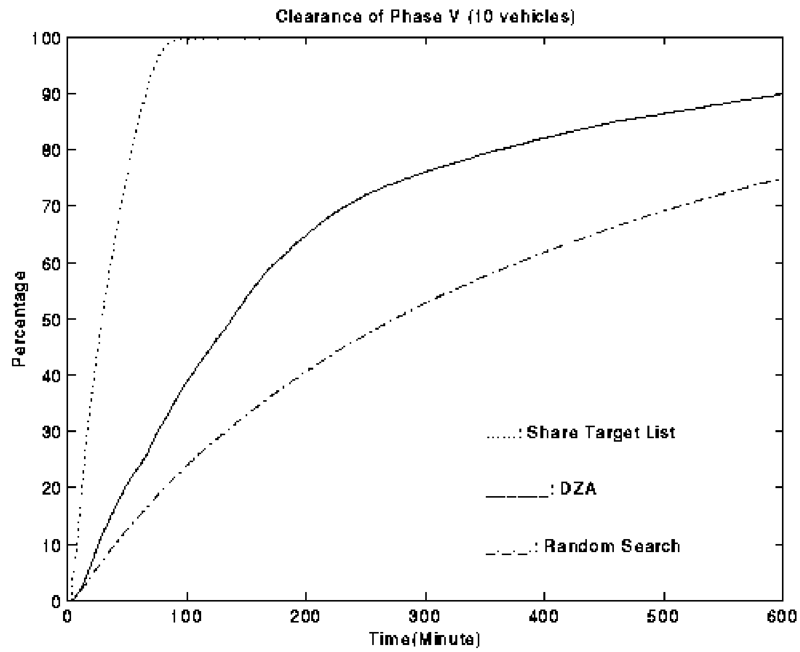

Clearance of Phase IV (10 vehicles)
Percentage
Time(Minute)
......: Share Target List
______: DZA
_._._.: Random Search

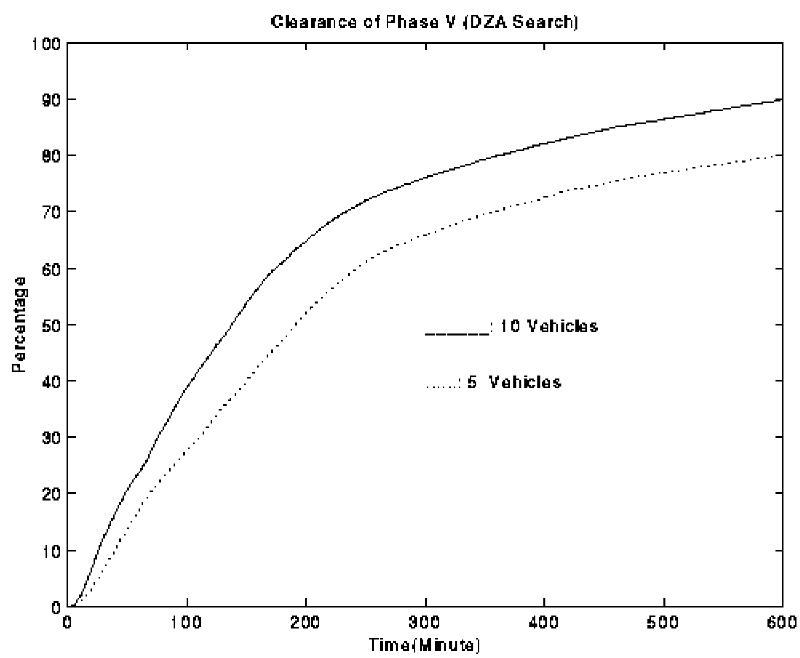

Clearance of Phase IV (DZA Search)
Percentage
Time(Minute)
______: 10 Vehicles
......: 5 Vehicles
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600


Example of Phase V (5 vehicles)
Meters
Meters
0
20
40
60
80
100
120
140
160
0
50
100
150


Clearance of Phase V (5 vehicles)
Percentage
Time(Minute)
......: Share Target List
______: DZA
_._._.: Random Search
0
10
20
30
40
50
60
70
80
90
100
0
100
200
300
400
500
600


Example of Phase V (10 vehicles)
Meters
Meters
0
20
40
60
80
100
120
140
160
0
50
100
150





5.0 CONCLUSIONS

It has been shown here that the clearance of a 150m by 150 m field with five possible cluster munition drops could be cleared using PUCA with multiple small robots. However, the time taken when using BUGS alone would exceed the expected endurance of small machines unless in excess of 50 or so machines were used.

The use of pre-targeting information is invaluable for the reduction of search area and in Phase V, for example, can be cleared by 10 vehicles in 90 minutes. The additional time to perform the targeting using Auto-Recorm has been analzed, and is given to be 100-140 minutes depending on the Phase and the algorithm used. It follows that an outside time would be between 190-230 minutes.

Using BUGs alone but with the Dynamics Zone Allocation methodology, ten BUGs could clear Phase V to 90% in 600 minutes - an improvement of the use of BUGs alone with no DZA, but not as fast as using the cooperative behavior between AUTO-RECORM and BUGs.

6.0 REFERENCES

[1] Healey, A. J., Kim, J., "BUGS: Robot Control, UXO and Minefield Clearance", Report # NPS-ME-96-005, Naval Postgraduate School, December 31, 1996.

[2] Healey, A. J., Kim, Y., "Control of Small Robotic Vehicles In Unexploded Ordnance Clearance", ***IEEE Proceedings, ICRA 97***, Albuquerque, New Mexico, 1997. http://web.nps.navy.mil/~me/healey/papers/icra_paper_97.pdf

[3] Healey, A. J. , Kim, J., "Modeling and Simulation Methodology for Reconnaissance in VSW Minefields with Multiple Autonomous Vehicles", Proceedings SPIE Conference, Orlando, FA, 1999